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The Public Affairs Office (PA) has reviewed this report and it is releasable to the National Technical Information Service (NTIS). At NTIS, the report will be made available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.

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This report summarizes research to develop operational requirements and design concepts for a new famlily of portable shelters (FOPS) that provide basic and upgradeable levels of protection from conventional weapon effects. The research focuses on identifying and reviewing applicable technology, developing and evaluating shelter concepts, and evaluating the deasibility of hardening the shelters against conventional weapon threats. The research products include a computational model for quantifying survivability from fragment effects, a multi-attribute shelter selection methodology, recommended shelter/hardening concepts, and a roadmap for shelter development.

The fragment hardening analyses show that although significant hardness levels can be achieved by incorporating modern ballistic composites such as Kevlar, Spectra, and S2-glass, it is not feasible to integrally hardenthe entire shelter to Splinter levels of protection. For the small personnel shelter, the air beam shelter and Modular Extendable Rigid-Wall Shelter (MERWS) concepts consistently rank at or near the top of the multi-attribute utility rankings. For large area shelters, the arch-supported panel and bin wall hangars are the leading concepts, except in cases where survivability is given little or no priority. In those cases, the air-and frame-supported fabric shelters excel.

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PREFACE

This report was prepared by Applied Research Associates, Inc. (ARA), Southeast Division, 6404 Falls of Neuse Road, Suite 200, Raleigh, North Carolina 27615, under contract F08635-88-C-0067, Subtask 2.13, for the Wright Laboratory Air Base Systems Branch, 139 Barnes Drive, Suite 2, Tyndall AFB, Florida, 32403-5323.

This report summarizes research to develop operational requirements and design concepts for a new family of portable shelters (FOPS) that provide basic and upgradeable levels of protection from conventional weapon effects. The research focuses on identifying and reviewing applicable technology, developing and evaluating shelter concepts, and evaluating the feasibility of hardening the shelters against conventional weapon threats. The research products include a computational model for quantifying survivability from fragment effects, a multi-attribute shelter selection methodology, recommended shelter/hardening concepts, and a roadmap for shelter development.

The performance period for this effort was from 1 June 1991 through 30 November 1992. The AFCESA/RACS project officers were Captain Diane B. Miller and Lieutenant Keith Westmoreland. Several military organizations, ballistic fiber manufacturers, and commercial shelter companies provided assistance in gathering data and information used in the research. These data are gratefully acknowledged and noted in the report.

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EXECUTIVE SUMMARY

A. OBJECTIVE

This report summarizes research on a new family of portable shelters (FOPS) for the United States Air Force (USAF). The main objective of the research is to develop operational requirements and optimal preliminary design concepts for airmobile shelters that provide basic and upgradeable levels of protection from conventional weapon effects. The basic shelter-hardening goal is Splinter Protection at a minimum, with upgradeable hardness to higher protection levels provided through optional hardening kits or methods. Specific objectives of the research include:

1. Develop operational requirements and prepare a preliminary working draft Operational Requirements Document (ORD);
2. Identify and evaluate relevant technologies and develop shelter concepts;
3. Evaluate hardening feasibility and determine achievable levels of protection;
4. Evaluate and screen shelter concepts to identify most promising concepts;
5. Perform trade-off and optimization studies; and
6. Recommend shelter/hardening concepts for development and prepare a roadmap for development/testing of the shelter/hardening concepts.

B. BACKGROUND

The need for a new family of portable shelters has been expressed by the Air Force (AF) shelter user community and is officially stated in the Air Force Statement of Need (SON) TAF SON 314-88 [USAF, 1990]. The primary purpose of the transportable shelters in the USAF inventory is to provide shelter for rapidly deployed forces in bare base situations or other similar settings. The current shelter inventory (Harvest Eagle, Harvest Bare, and Harvest Falcon assets) require replacement in the near future, providing an opportunity to develop new shelter designs that provide protection against conventional weapon effects.

Current portable shelters were primarily designed to address three critical design considerations: mobility, operability/maintainability, and cost. Improved operability in high threat areas, specifically protection from chemical-biological warfare (CBW), is an additional design consideration reflected in the more recent additions to the shelter inventory. However, existing shelters offer little or no protection against small arms and fragment threats. Significant advances in materials technologies have occurred since the current shelters were developed, providing the opportunity to incorporate ballistic protection in the new FOPS without unduly compromising shelter mobility.

C. SCOPE

The research focuses on identifying and reviewing applicable technology, developing and evaluating shelter concepts, and evaluating the feasibility of hardening the shelters against conventional weapon threats. The primary end products of the research are the recommended shelter concepts and a roadmap for development and testing of the shelters. Additional products of the research are: (1) a working draft of the ORD, (2) an assessment of current technology with respect to portable shelters and methods for hardening lightweight shelters, (3) an improved methodology for evaluating the survivability of structures for fragment effects, (4) an assessment of the feasibility of hardening FOPS, (5) a multiattribute decision analysis methodology for evaluating and ranking shelter concepts, and (6) results of preliminary trade and optimization studies.

D. METHODOLOGY

1. Task 1: Definition of Operational Requirements

Under this task we developed the operational requirements for FOPS. To formalize the operational needs specified in TAF SON 314-88, we reviewed the current inventory of modular and expandable shelters and visited over a dozen user and support agencies to gather data on current shelter performance, perceived deficiencies, and desired attributes for FOPS. On the basis of our review, we prepared a working draft ORD. We also identified conflicting shelter performance priorities within the Air Force and recommended that a FOPS Requirements Working Group (RWG) meeting be held to review the draft ORD and form an Air Force consensus on shelter priorities. This meeting was held on 14-15 February 1992. A FOPS survey was subsequently prepared and distributed to the RWG attendees soliciting their comments and inputs on the relative importance of the major shelter requirements. The RWG survey results provided the basis for one of the preference sets used in the shelter evaluation presented in Task 4.

2. Task 2: Shelter Concept Synthesis

We reviewed relevant shelter technologies and synthesized possible shelter and hardening concepts through a systematic procedure that included literature reviews; computerized database searches; and visits to relevant laboratories, researchers, and practitioners. Based on the results of this technology survey, we developed a total of 24 small and large span shelter concepts for evaluation. For the purposes of this study, the term *shelter concept* included the following design features: (1) geometry (size and shape), (2) structural system, (3) cladding system (soft- or hard-wall), (4) materials, (5) integral and/or upgraded hardening systems, (6) packaging, (7) assembly characteristics (rate and skill/equipment requirements), and (8) estimated cost. These basic design features encompass key operational issues and constraints for the candidate airmobile shelter concepts that must be quantitatively assessed before detailed design and validation studies of selected concepts can begin.

3. Task 3: Hardness Analysis

The SON and ORD for FOPS require Splinter Protection as a minimum with Semihardened Protection a goal for high value shelters. Under this task, we developed the necessary analysis tools and performed a preliminary assessment of the feasibility of hardening FOPS against small arms fire and the airblast and fragmentation effects of conventional munitions. Fragmentation, being the controlling weapon effect for lightly protected structures, was the focus of our hardening analyses.

The analysis of fragment hardening feasibility for FOPS required the development and implementation of new analysis models for weapons effects data and perforation resistance. Current design procedures, such as those presented in the *Lightweight Armor Design Handbook* [MTL, 1990] and the *Air Force Protective Construction Design Manual* (*PCDM*) [Drake, *et al.*, 1989], were inadequate in that: (1) they consider only the fragment weight distribution and do not consider the number of fragments generated or the probability that critical fragments will strike the target at the specified standoff; (2) the weapon characteristics are overly conservative because they generate larger average fragment weights and higher initial velocities than observed in arena testing; and (3) the methods do not provide a means for evaluating the survival probability stated in the Splinter Protection and Semihardened Protection threat definitions. Use of the traditional fragment analysis procedures would therefore provide biased and incorrect analyses of airmobile shelter concepts and would not permit evaluation of survival levels *vis a vis* Air Force specified threats.

The new analysis methodology, termed SAFE (Survivability Assessment for Fragment Effects), models the weapon fragment weights, velocities, and ejection angles based on arena test data for the selected munition. The munition surface is discretized into series of cells and mapped onto the target surface using straight line trajectories. Output quantities calculated include the bomb cell impact points on the target surface; critical fragment weight, impact angle, and striking velocity; and number of perforations. SAFE is used to perform a preliminary assessment of the fragment hardening feasibility for FOPS. As part of this assessment, we developed fragment models for six munitions that represent a spectrum of potential weapon threats for FOPS: (1) a 1000-*pound* bomb, (2) a 40-*mm* aircraft (A/C) cannon, (3) a cluster munition, (4) a 152/155-*mm* artillery round, (5) a 122-*mm* rocket, and (6) a 250-*pound* missile. We also developed empirical Thor perforation models for Kevlar® KM2, Spectra®, and S2-glass fabrics and panels.

4. Task 4: Concept Evaluation, Screening, and Selection

We developed and implemented the Airmobile Shelter Evaluation Methodology (ASEM) code, a multiattribute decision analysis tool, for selecting the most promising design concepts. Three major tasks are involved in selecting the leading concepts: (1) developing a set of design attributes that characterizes each basic or upgraded shelter concept, (2) evaluating these design attributes, and (3) implementing a decision analysis methodology that models the conflicting design objectives specified in the FOPS ORD. Since the selection of the "best" shelter concept depends on the relative priority or weight assigned to each of the design objectives, we considered four different preference sets: (1) preferences based on the RWG survey, (2) an Equal preference set (*i.e.*, mobility, cost, performance and survivability equally important), (3) a No-Cost preference set, and (4) a No-Survivability preference set. The latter two cases represent bounding sets in which one major objective is given zero weight and the remaining three are weighted equally.

5. Task 5: Trade Studies and Optimization

The trade studies and optimization task provided supporting calculations for quantifying the basic and upgraded shelter attributes, preliminary optimization studies on shelter geometry, an assessment of shelter heating and cooling loads, and an analysis of the sensitivity of shelter selection to uncertainties in decision maker preferences.

E. RESULTS AND CONCLUSIONS

1. Hardening

Methods considered in the hardness analysis include: integral, field installable upgrades, and field expedient upgrades. Integral hardness is defined as the inherent hardness of the basic shelter and can be provided through the use of ballistic fabrics or panels in the basic shelter design. Field installable upgrades consist of lightweight armors that are added to the shelter in the field. These upgrades can be either shelter supported or free standing. Several ballistic hardened panel concepts suitable for integral or field installable upgrades are proposed in the study. Field expedient hardening upgrades include conventional hardenings systems such as soil berms, soil bins, sand bags, and concrete revetments. These hardening upgrades can also be integral (as in the case of bin-wall and reinforced earth shelters) or field expedient. Areal densities considered for the fabric and panel upgrades ranged from 1 to 8 *psf* (16 and 32 *psf* densities were calculated for selected cases) while soil thicknesses were varied from 1 to 4 *feet*.

Although significant hardness levels can be achieved by incorporating modern ballistic composites such as Kevlar®, Spectra®, and S2-glass, our results show that it is not feasible to integrally harden the entire shelter to Splinter levels of protection. The three composite materials (fabric or panel) provide comparable levels of protection and are as effective as twice the areal density of aluminum; however, they are not capable of stopping the large, high-speed fragments generated by the bomb and missile at realistic areal densities. Appendix H shows that Splinter Protection can be provided for the A/C cannon and rocket at reasonable areal densities, but that areal densities required for the missile and bomb are excessive. These results emphasize the varying severity of the four weapon types encompassed by Splinter Protection and the difficulty in achieving Splinter Protection for the large munitions. Only the soil bin walls and soil berms are capable of providing Splinter level protection at low costs.

The heavy panel weights required for ballistic protection will significantly degrade shelter transportability and erection times. Selective hardening offers an alternative to integrally hardening the entire shelter. Selective hardening concentrates ballistic materials into dedicated "safe" areas that provide very high levels of protection. SAFE results show that by concentrating ballistic composite materials into the lower 2 *feet* of a panel, "Splinter Protection" can be achieved. In practice, providing this "Splinter Protection" over the bottom 2 *feet* will require segmenting the panel height for handling and erection.

2. Shelter Concept Synthesis and Evaluation

Our concept development approach was to systematically identify a wide range of design alternatives for each of the major shelter subsystems (*i.e.*, geometry, structural system, cladding system, and hardening upgrades). Although we do propose hardening-related shelter design modifications for some of the design concepts (*i.e.*, hybrid panel/fabric claddings and soil-filled walls), most of the basic concepts assessed in this study are either currently in use or under development. The remaining concepts have either been published previously, or they are portable shelter adaptations of existing construction techniques.

There are significant uncertainties and subjective judgments associated with the ASEM inputs used in the shelter evaluation; however, AF prioritization of the competing shelter objectives stands out as the dominant source of shelter selection uncertainty. The sensitivity analysis results suggest that the RWG preferences fall at or near a crossover point in the overall utility concepts. A stronger consensus either for or against hardening will produce clear differences in the leading shelter concepts. Without this consensus, we believe that the most effective design solutions will be upgradeable, adaptable shelter concepts. Thus, a major challenge will be to minimize the number of different shelter components so that inventory demands are minimized.

a. Small Shelter Results.

Two concepts appear most frequently at the top of the small shelter overall utility rankings: the basic air beam fabric shelter and the upgraded airmobile Modular Extendable Rigid Wall Shelter configurations. Under two of the four preference sets (RWG and No-Survivability), the leading concept is the basic air beam-supported fabric shelter. For the RWG scaling, the air beam is followed by the basic pole-supported tent and the soil bin upgraded airmobile MERWS concept. The third tier of concepts includes the basic dual wall and air-supported fabric shelter concepts as well as the S2-glass panel and Spectra® blanket upgraded airmobile MERWS concepts. Under the No-Survivability preference set, fabric shelters make up the top five concepts, followed by the basic airmobile MERWS and hybrid MERWS concepts. Under the Equal and No-Cost preference sets, the airmobile MERWS concept with the free-standing 36-*inch* soil bin upgrade is the highest rated concept followed by six other soil hardened concepts. If soil-protected shelter concepts are excluded, the MERWS with shelter-supported S2-glass panels or Spectra® blanket upgrades and the basic air beam shelter become the recommended concepts under Equal scaling. Of the nonfabric shelters, the airmobile MERWS concept is the leading overall concept for all four preference sets.

b. Large Shelter Results.

Under three of the four preference sets used in the shelter evaluation studies, the basic and upgraded arch-supported panel and bin wall hangars are consistently ranked as the leading concepts. The No-Survivability preference set is the only case under which the arch/panel and bin wall concepts do not rate the best. When survivability is given little or no priority, the basic air beam and frame-supported fabric shelter concepts excel. However, even under the No-Survivability preference set, the basic arch/panel and bin wall hangar concepts are competitive with the fabric hangar concepts. For the arch/panel concept, the utilities of soil bin, S2-glass panel, and Spectra® blanket upgrade configurations approximately meet or exceed the overall utilities of the basic, unhardened concept. For the bin wall concept, the only upgrade considered is an increased wall thickness with 36 *inches* of soil infill. The overall utility of the upgraded bin wall concept is also similar to or better than that of the basic bin wall concept (which has only 12 *inches* of soil). In both cases, the relative utilities of the hardening upgrades improve as the importance placed on survivability is increased.

F. RECOMMENDATIONS

1. Hardening

We recommend that the basic shelter be hardened to provide integral protection against small fragmenting munitions and be designed to support field installable or expedient methods against larger weapons. SAFE results show that small areal densities (*i.e.*, 2 to 3 *psf*) of composite material are effective in stopping fragments from antipersonnel munitions such as A/C cannon fire and cluster munitions and also provide protection from most small arms fire. These areal densities can be easily incorporated into the shelter design and we recommend that this level of protection be provided as an integral feature of the shelter design.

To resist combined airblast and fragment impulses, the structural system must be capable of supporting the dynamic loads imparted via the shelter shell. Shelter concepts with modular load bearing panels, such as MERWS, do not employ a frame as part of the structural support system and must transfer loads through discrete connectors. These shelters are susceptible to collapse by lateral side sway which limits their airblast resistance. Consequently, we recommend modifying MERWS to incorporate a frame structure.

2. Shelter Concepts

a. Small Shelter

For the small shelter, we recommend that the hardened airmobile MERWS concept be the focus of the next phase of the research program. If satisfactory hardening levels cannot be achieved or if the mobility and cost penalties prove to be beyond AF constraints, we recommend that a new generation of unhardened air beam (*i.e.*, pressurized rib) supported fabric shelters be pursued as a high payoff approach to shelter mobility and cost.[1] A low risk alternative fabric concept that rates better with respect to performance and structural reliability is the frame-supported fabric concept. The hardening technology developed under further research for the MERWS system will also be directly applicable to an upgraded frame-supported hybrid fabric/panel concept. Thus, the frame-supported fabric concept should be kept under consideration as a low-risk back-up alternative.

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[1]The transportability threshold is to be determined in a future revision of the ORD. It is possible that the MERWS may not meet this threshold due to its relatively low packing ratio.

b. Large Shelter

For the large shelter, we recommend that the arch/panel and bin wall hangar concepts be studied in parallel. The arch/panel concept is basically an upgraded version of the current Harvest Bare ACH shelter and preliminary design should be relatively straightforward. In addition, the experimental program for panel hardening is applicable to the arch/panel hangar. Since the preferred portable hangar concept will ultimately depend on whether our estimates for the bin wall design attributes can be met, we also recommend that a preliminary structural design and analysis of the basic and upgraded bin wall concepts be developed. The feasibility of the bin wall concept will be determined by three key issues: (1) the required hardness level, (2) the acceptability of soil-based hardening methods, and (3) the developmental uncertainties associated with the bin wall hangar concept. After a more detailed cycle of design and analysis on the arch/panel and bin wall hangar concepts is complete, a re-evaluation of the two concepts should be performed. As with the small shelter recommendations, the mobility and cost penalties associated with shelter hardening may lead Air Force decision makers to abandon the goal of hardened portable shelters. In this case, the No-Survivability preference set would be the most applicable model, and we would recommend that the basic air beam hangar concept be pursued as a high risk/payoff approach to shelter mobility and cost with a low risk back-up alternative being the frame-supported fabric hangar concept.

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SECTION I

INTRODUCTION

A. OBJECTIVE

This report summarizes research on a new family of portable shelters (FOPS) for the United States Air Force (USAF).[1] The main objective of the research is to develop operational requirements and optimal preliminary design concepts for airmobile shelters that provide basic and upgradeable levels of protection from conventional weapon effects. The basic shelter-hardening goal is Splinter Protection at a minimum, with upgradeable hardness to higher protection levels provided through optional hardening kits or methods. The research focuses on identifying and reviewing applicable technology, developing and evaluating shelter concepts, and evaluating the feasibility of hardening the shelters against conventional weapon threats. Specific objectives include:

1. Develop operational requirements and prepare a preliminary working draft ORD;
2. Identify and evaluate relevant technologies and develop shelter concepts;
3. Evaluate hardening feasibility and determine achievable levels of protection;
4. Evaluate and screen shelter concepts to identify most promising concepts;
5. Perform trade-off and optimization studies; and
6. Recommend shelter and hardening concepts for follow-on development and prepare a roadmap for development and testing of the shelter and hardening concepts.

B BACKGROUND

The need for a new family of portable shelters has been expressed by the Air Force (AF) shelter user community and is officially stated in the Air Force Statement of Need (SON) TAF SON 314-88 [USAF, 1990]. Basic USAF doctrine identifies the need for flexibility, responsiveness, and mobility of Air Force tactical forces. The primary purpose of the transportable shelters in the USAF inventory is to provide shelter for rapidly deployed forces in bare base situations or other similar settings. Shelters in the current inventory include Harvest Eagle, Harvest Bare, and Harvest Falcon assets. These shelters will require replacement in the near future, providing an opportunity to develop new shelter designs that provide protection against conventional weapon effects.

The current generation of Air Force portable shelters was primarily designed to address three broad categories of critical design considerations: mobility, operability and maintainability, and cost. Mobility includes both transportability (*i.e.*, airlift, sealift, and ground transportation) and rapid assembly/disassembly of the shelters. Operability and maintainability include a wide array of issues such as: reliability, durability, service life, shelf-life, functionality, versatility, modularity, safety (*e.g.*, flammability and ventilation), habitability, and design environmental loads (*e.g.*, temperature, wind, snow, rain, humidity, etc.). Cost considerations include low initial unit cost, low operation and maintenance costs, low redeployment costs (*i.e.*, replacement of

[1] A glossary of airmobile shelter terms and acronyms is presented in Appendix A.

lost or non-reusable parts and other reconstitution costs), and low storage costs. Cost can also be evaluated in terms of an overall life cycle cost estimate if sufficient information is available. These three broad categories correspond to competing and often conflicting objectives and constraints: logistics officers place primary emphasis on mobility, shelter program managers rank shelter cost highest, and field personnel place highest priority on habitability, operability, and maintainability.

Improved operability in high-threat areas, specifically protection from chemical-biological warfare (CBW), is an additional design consideration reflected in the more recent additions to the shelter inventory. Generally, these improvements have been in the form of retrofit kits consisting of CBW-resistant liners, overpressure and filtering equipment, and decontamination modules. However, the existing shelters offer little or no direct protection against small arms and fragment threats. Significant advances in materials technologies have occurred during the period since the current shelters were developed. As a result, there is now an opportunity to provide some level of ballistic protection in the new family of shelters without unduly compromising shelter mobility. Therefore, the major new issue to be investigated in this research is to determine and define the levels of integral and/or upgraded hardening that may be feasible in the new family of shelters.

C. APPROACH

Our approach to identifying and evaluating the most promising shelter and hardening concepts for FOPS consists of five basic tasks, as illustrated in Figure 1: (1) Definition of Operational Requirements; (2) Shelter Concept Synthesis; (3) Hardness Analysis; (4) Concept Evaluation, Screening, and Selection; and (5) Trade Studies and Optimization. These five tasks provide for the definition of operational requirements for FOPS; review of relevant technology on portable shelters, materials research, weapon effects, and hardening concepts; the synthesis of this technology into shelter and hardening concepts; and the screening, evaluation, and selection of recommended shelter concepts for follow-on development. The first step in developing a structural design concept for the new shelters is to define the loads the shelter must support. The magnitude of these loads is heavily dependent on the fragment hardening system. Consequently, the structural analysis in this study focused on the hardening methods and loads required to provide Splinter Protection.

The primary end products of the research are the recommended shelter concepts and a roadmap for development and testing of the shelters. Additional products of the research are (1) a working draft of the Operational Requirements Document (ORD), (2) an assessment of current technology with respect to portable shelters and methods for hardening lightweight shelters, (3) an improved methodology for evaluating the survivability of structures for fragment effects, (4) an assessment of the feasibility of hardening FOPS, (5) a multiattribute decision analysis methodology for evaluating and ranking shelter concepts, and (6) results of preliminary trade and optimization studies.

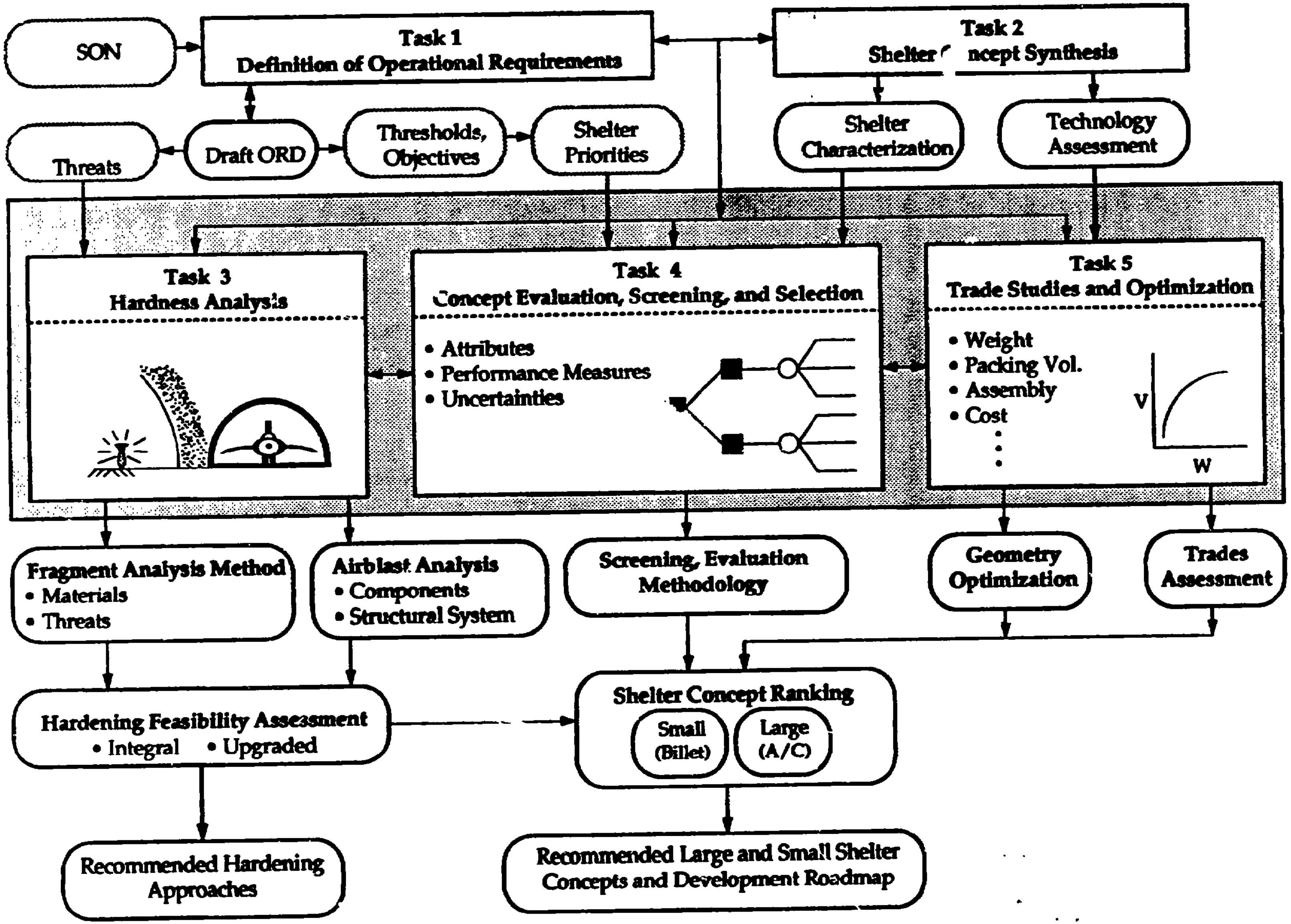


Figure 1. Project Research Tasks and End Products

1. Task 1: Definition of Operational Requirements

The objective of this task was to develop the operational requirements for FOPS. TAF SON 314-88 [USAF, 1990] provided the baseline requirements (thresholds) and objectives (goals) for this effort. To evaluate and refine these operational requirements, we reviewed the current inventory of modular and expandable shelters and visited several user and support agencies to gather data on current shelter performance, perceived deficiencies (including feedback from DESERT SHIELD and DESERT STORM), and desired attributes for FOPS. Table 1 summarizes the agencies contacted or visited. Section I.D summarizes the key issues identified during these visits and as a result of subsequent interaction with members of the Air Force portable shelter community.

On the basis of our interactions with AF users and the preliminary results from the technology survey, hardness analysis, and trade studies, we prepared and presented a draft Operational Requirements Document (ORD). The ORD enumerates specific system performance requirements and ultimately serves as the basis for accepting or rejecting the proposed system. We also identified conflicting shelter performance priorities within the Air Force portable shelter community and recommended that a meeting be held to review the draft ORD and form an Air Force consensus on shelter priorities. This recommendation resulted in the FOPS Requirements Working Group (RWG) meeting on 14-15 February 1992. At the RWG meeting the draft ORD was reviewed and adopted by the Air Force and is now being processed through the Air Force chain of command. Appendix B presents the most recent draft ORD.

Many of the shelter requirements specified in the SON and ORD are conflicting and cannot be satisfied simultaneously. For example, the hardening objective for FOPS requires additional mass to resist fragment perforation that conflicts with the requirements for low weight, mobility, and rapid assembly. The relative importance of these objectives remained unresolved after the RWG meeting. To further explore this issue, we prepared and distributed a survey to the RWG attendees soliciting their comments and inputs on the relative importance of the major shelter requirements. Appendix C summarizes the results from this survey. The RWG survey results provided the basis for one of the four preference sets used in the shelter evaluation presented in Section V.

2. Task 2: Shelter Concept Synthesis

The objective of this task was to synthesize possible solutions to the design problem through a systematic procedure that included literature reviews; computerized database searches; and visits to relevant laboratories, researchers, and practitioners. This review focused on identifying and evaluating combinations of materials and technologies in an attempt to identify innovative and cost-effective concepts that take advantage of advanced materials, structural geometries and systems, and fabrication technologies. Section II summarizes the results of this technology survey and presents 24 small and large shelter concepts for evaluation under Task 4.

TABLE 1. GOVERNMENT AGENCIES VISITED OR CONTACTED.

Agency	Topics
AIR FORCE	
AFCESA	Weapon effects Hardening technology Bare base planning and operations
WL/ASD - UDRI	Tactical shelter R&D Shelter materials research
ESD	AF tactical shelters
TAC	Operational requirements Shelter experience
Robbins AFB	Bare Base Systems Management Office
CENTAF	DESERT STORM bare base experience Shelter logistics
ARMY	
NRDEC	Army tentage Chemical/Biological protection Tactical shelters Personnel protection
MTL	Ballistic protection Lightweight armor
WES	Expedient protection
CERL	Expedient shelter research Foam domes
MICOM	DESERT STORM foam domes and arches
NAVY	
MCRDAC	Tactical shelters
NCEL	ABSEP shelter section program

For the purposes of this study, the term *shelter concept* includes the following design features: (1) geometry (size and shape), (2) structural system, (3) cladding system (soft- or hard-wall), (4) materials, (5) integral and/or upgraded hardening systems, (6) packaging, (7) assembly characteristics (rate and skill/equipment requirements), and (8) estimated cost.[1] These basic design features encompass key operational issues and constraints for the candidate airmobile shelter concepts that must be quantitatively assessed before detailed design and validation studies of selected concepts can begin.

3. Task 3: Hardness Analysis

Under the Air Force policy of Global Reach/Global Power, FOPS may be deployed into high-threat areas. Under these circumstances, FOPS must be capable of providing protection against the airblast and fragmentation effects of conventional munitions, ballistic penetration from

[1]Two basic shelter sizes are considered in this study: a small shelter with at least 600 $feet^2$ of usable floor space (8-*foot* vertical clearance) and an aircraft maintenance hangar with at least 4800 $feet^2$ of usable floor space (15-*foot* vertical clearance, minimum).

small arms fire, and infiltration by chemical/biological (CB) agents. The SON and ORD for FOPS require Splinter Protection as a minimum with Semihardened Protection a goal for high value shelters in addition to CB protection. Under this task, we developed the necessary analysis tools and performed a preliminary assessment of the feasibility of hardening FOPS against small arms fire and the airblast and fragmentation effects of conventional munitions. Fragmentation is the controlling weapon effect for lightly armored structures/vehicles; hence, our analysis focused on fragmentation protection. CB protection can be engineered for all the shelter concepts considered. Consequently, CB protection does not impact the concept evaluation and selection process in this initial study. CB protection will require design consideration early in the prototype design and development phase.

Three classes of fragment-hardening methods are presented in Section III.C: integral, field installable, and field expedient upgrades. Integral hardness is defined as the inherent hardness of the basic shelter and can be provided through the use of ballistic fabrics or panels in the basic shelter design. Field-installable upgrades consist of lightweight armors added to the shelter in the field. These upgrades can be either shelter supported or free standing. Several ballistic hardened panel concepts suitable for integral or field installable upgrades are proposed in Section III.C. Field expedient hardening upgrades include conventional hardenings systems such as: soil berms and bins; sand bags and grids; and concrete panels and revetments. Representative hardening upgrades from each of these three classes are included in the shelter evaluations conducted under Task 4.

The analysis of fragment hardening feasibility for FOPS required the development and implementation of new analysis models for weapons effects data and perforation resistance. Design procedures for lightweight armor use empirical perforation curves and are not available for new fiber and resin formulations recently introduced for Kevlar, Spectra®, and S2-glass. Ballistic data for these materials is limited and often targeted at specific applications, such as lightweight personnel armor (vests and helmets). Typical areal densities for these applications fall between 1 and 2 *psf*, much less than the areal densities required to stop fragments from a general purpose (GP) bomb. Only S2-glass had data available in the 8 to 30 *psf* areal density range that may be required for FOPS. Lightweight armor design requires a specific projectile and specific striking velocity. Since the threat levels for Splinter Protection and Semihardened Protection are specified in terms of probability of survival for specific weapons at specific standoffs, we developed analytical models for determining the critical fragment weight and striking velocity.

Design procedures for specifying the critical fragment weight, such as those presented in the *Protective Construction Design Manual* (*PCDM*) [Drake, *et. al*, 1989] consider only the fragment weight distribution and do not consider the number of fragments generated or the probability that the critical fragment will strike the target at the specified standoff [Twisdale, *et al.*, 1992]. The weapon characteristics presented in the *PCDM* are also overly conservative in that they generate larger average fragment weights and higher initial velocities than observed in arena testing. Use of the traditional fragment analysis procedures in the *PCDM* would therefore provide biased and incorrect analyses of airmobile shelter concepts. Further, we would not be able to determine if the required levels of survivability would be satisfied *vis a vis* the Air Force specified threats.

Consequently, we developed an analysis tool specifically for the hardness analysis required for airmobile shelter concept evaluation. The developed methodology is termed SAFE (Survivability Assessment for Fragment Effects) and is presented in Section III. SAFE models the weapon as an axisymmetric line source along the axis of the munition with fragment weights, velocities, and ejection angles based on arena test data for the selected munition. The munition surface is discretized into series of cells and mapped onto the target surface using straight line trajectories. Output quantities calculated include a mapping of the bomb cell impact points on the target surface; critical fragment weight, impact angle, and striking velocity; number of impacts and perforations; and momentum transferred to the target. Local perforation response is modeled using semi-empirical perforation models, such as the Thor equations. We calculate the critical fragment weight (W_{50}) for perforation using bisection considering the effects of impact obliquity, velocity decay due to drag, and perforation resistance of the wall material. The critical fragment weight, in combination with the fragment weight distribution and impact conditions, provides the expected number of fragment perforations and the momentum transferred to the target.

We use the SAFE code in Section III to perform a preliminary assessment of the fragment hardening feasibility for FOPS. As part of this assessment, we developed SAFE fragment models for six munitions that represent a spectrum of potential weapon threats for FOPS: (1) a 1000-*pound* bomb, (2) a 40-*mm* aircraft (A/C) cannon, (3) a cluster munition, (4) a 152/155-*mm* artillery round, (5) a 122-*mm* rocket, and (6) a 250-*pound* missile. Appendix G of Volume II summarizes the fragmentation models for weapons (2) through (6). We also developed preliminary Thor perforation models for Kevlar® KM2, Spectra®, and S2-glass composite materials using limited data provided by the fiber manufacturers. The results of the analysis presented in Section III are interpreted in terms of Splinter Protection in Volume II, Appendix H.

4. Task 4: Concept Evaluation, Screening, and Selection

The objectives of the fourth task were to develop and implement a methodology for selecting the most promising design concepts. There are three major subtasks involved in the selection of the leading concepts: (1) developing a complete set of design attributes that adequately describes the characteristics of an extremely diverse array of basic and upgraded shelter concepts, (2) estimating the value of each design variable for each of the candidate shelter concepts, and (3) implementing a decision analysis methodology that models the severely conflicting design objectives specified in the FOPS ORD.

In Section IV, we define a hierarchy of shelter attributes that encompasses each of the major design objectives. The estimates for each design attribute are based on the review of existing technology (Task 2), the operational requirements (Task 1), the hardness analyses (Task 3), and the shelter trade studies (Task 5). Since the selection of the "best" shelter concept may vary significantly depending on the relative priority or weight assigned to each of the design objectives, we consider several different perspectives on shelter priorities. The attribute h . hy, the concept design attributes the attribute utility functions, and objective preference sets form the four major inputs to the Airmobile Shelter Evaluation Methodology (ASEM) code. ASEM is a multi-attribute decision tool based on utility theory that we developed specifically for this task and for performing updated concept evaluations throughout the entire FOPS research and development program. Sections IV and V summarize the results of the ASEM analyses. Appendix D provides a detailed description of the ASEM code.

5. Task 5: Trade Studies and Optimization

Under this task, we quantify the shelter attributes used in the concept screening and evaluation studies. The estimated attribute values for each concept are based on an extensive database of existing shelter attributes collected during our interactions with shelter users and during our literature review and are supplemented with additional scoping calculations, as needed. Sections II and IV present attribute estimates for the basic and upgraded shelter concepts considered. A preliminary trade study on the effect of insulating the shelter walls was performed and is presented in Appendix E. The R-value trade study investigates the possibility of reducing environmental control equipment airlift demand by improving the thermal properties of the new shelters. In addition, we performed a shelter geometry optimization study to determine optimum shelter dimensions that minimized surface area (excluding the floor) for a given volume. Results are expressed in terms of a non-dimensional surface area efficiency parameter, $S_e = S/V^{2/3}$ (S = surface area and V = internal volume). The resulting shapes were evaluated for relative protection against projectile damage where damage was assumed to be proportional to the projected surface area and projectile strike angle. Appendix F presents the results of the shelter geometry optimization study. The final activity conducted under Task 5 is the sensitivity analysis of the leading small and large shelter concepts which is presented in Section IV.F. These studies assess the impact of uncertainties in decision maker priorities on the selection of recommended design concepts. Key parameters varied in the sensitivity studies are the priority placed on shelter survivability and the curvatures of the packing ratio and perforation density utility functions. Changes in overall shelter rankings are discussed for each of the parameters varied in the sensitivity studies.

D. DEFINITION OF OPERATIONAL REQUIREMENTS

In this section, we briefly summarize the results of Task 1, Definition of Operational Requirements. The major products of this task were a working draft ORD for the new FOPS and a survey of AF portable shelter users. Although research conducted under all five of the tasks outlined in Section C contributed significantly to our development of the working draft ORD (*e.g.*, the technology review, the preliminary trade studies, the decision analysis model, etc.), our summary of Task 1 is restricted to the following major activities: (1) visits and/or contacts with DOD shelter developers and users, (2) the development of the draft ORD, (3) the portable shelter RWG meeting, and (4) the RWG follow-up survey.

1. Interaction with DOD Shelter Developers and Users

Over the first several months of this study, we visited or contacted over a dozen different Air Force, Army, and Navy organizations that are involved with portable shelters. These contacts were summarized in Table 1. Key issues and comments arising from these contacts are summarized in the following paragraphs.

The primary purpose of our interactions with shelter developers and users was to get direct user inputs on operational requirements for FOPS and to avoid overlooking significant design requirements. Our discussions with AF shelter users highlighted the severe conflicts between FOPS design requirements. We were advised that the new FOPS must have lower airlift demand, faster erection times, lower cost, better durability, and improved habitability in comparison to the current generation of portable shelters. Since, the SON requirement of Splinter Protection directly conflicts with most of these requirements, we quickly realized that the optimal design concepts would depend heavily on the relative importance attached to each of these design objectives.

The current state-of-practice and the current state-of-the-art in portable shelters were the subjects of several of our visits and contacts. Often, these visits provided us an opportunity to tour and inspect current and/or developmental DOD portable shelters, including AF bare base shelters, Army tentage, and DOD tactical shelters. We also gathered specific design attributes (*i.e.*, cost, weight, packing ratio, and assembly times) for a large percentage of the current inventory of portable shelters, and we reviewed existing military standards for tactical shelter performance. Tentage selection and shelter selection studies conducted at the Army Natick Research, Development, and Engineering Center (NRDEC) and the Naval Civil Engineering Laboratory (NCEL) provided us examples and lessons learned from past shelter assessments.

Our visits gave us an opportunity to speak with experts in the areas of bare base planning and logistics. The readiness division of the AF Civil Engineering Support Agency (AFESA), for example, provided background information on bare base planning, data on existing portable shelters, and several points-of-contact within the portable shelter user community. At Shaw AFB, USCENTAF (U.S. Central A.F.) personnel related portable shelter and bare base deployments experiences gained from Operation DESERT SHIELD/DESERT STORM. Additional shelter logistics concerns were discussed at the Tactical Air Command (TAC) and at the Bare Base Systems Management Office.

An extremely important component of the new FOPS will be advanced materials. NRDEC provided key information on composite armors for individual protection, and the Materials Technology Laboratory (MTL) shared their database of lightweight armor materials with us. Modeling methods for ballistic composites were also discussed at the AF Wright Laboratories (WL) and the University of Dayton Research Institute (UDRI). These discussions also covered the specification of design fragments, military standards for Fragment Simulating Projectiles (FSPs), and possible testing opportunities for validating candidate hardening concepts.

The specification of design threats and the characterization of their effects are very important issues in the development of a hardened FOPS. In addition to providing overall direction to this research effort, the Airbase Survivability Branch of AFCESA assisted in specifying the portable shelter design threats evaluated in Section III. We discussed air base operability (ABO) issues, munitions area effectiveness models, and arena test procedures with AF personnel at Eglin AFB. Field expedient hardening methods and the Army Battlefield Survivability Field Manual [Army, 1985] were discussed with personnel at the Army Waterways Experiment Station (WES).

During our visit to TAC, we also reviewed the AF operational requirements process. We were advised to avoid over-specifying the design requirements since this can constrain shelter development and produce suboptimal results. We concluded that a partial solution to this problem is to make the shelters adaptable (*i.e.*, upgradeable) to satisfy extreme conditions.

2. Working Draft ORD

On 30 November 1991, we submitted a working draft ORD for the new FOPS to AFCESA and TAC. The document enumerated our preliminary recommendations on design thresholds and objectives for FOPS in the ORD format specified by AF Regulation 57-1. The primary information sources for the working draft ORD were the FOPS SON, our review of current technology, and our interactions with members of the DOD portable shelter community. The working draft ORD was ultimately adopted as the basis for the RWG draft ORD. Summaries of the portable shelter RWG meeting and the revised draft ORD are given in the following subsection.

3. Portable Shelter RWG Meeting

At the 13 November 1991 project review meeting, we recommended that a meeting of AF shelter users be convened to: (1) review and comment on the draft ORD discussed in the preceding subsection, and (2) prioritize the competing objectives that were emerging in draft ORD. As a result, the AFCESA readiness directorate (DX) and air base survivability branch (RACS) organized the Requirements documents Working Group (RWG) meeting which was held at Tyndall AFB during the week of 10 February 1992. The RWG meeting brought together representatives of five major AF commands (TAC, CENTAF, PACAF, USAFE, and SOUTHAF) to produce a user-coordinated working draft ORD for portable shelters, environmental control units, and rapid utility repair kits. The portable shelter ORD sessions were held during the first two days of the RWG meeting.

The outcome of the RWG meeting was a completed draft ORD that is now being processed through the AF chain of command. A copy of the July 1992 version of the FOPS ORD is included as Appendix B. Important design requirements specified in the ORD with respect to this research effort are:

- ***Shelter functions:*** billets, command and control, administration, maintenance shops, warehousing, medical, kitchens, dining halls, shower/latrines, and aircraft maintenance hangars.

- Standardized designs and components are a system objective.

- ***Erection rates:*** 1 *man-hour* per 75 *feet*^{2} threshold and 1 *man-hour* per 100 *feet*^{2} objective for personnel shelters; a threshold of not more than 120 *man-hours* for aircraft maintenance hangars (80 *man-hour* objective).

- ***Protection level:*** Splinter Protection as a threshold and Semihardened Protection upgrade kits as an objective.

- Chemical/Biological protection as an integral feature of the shelters or via upgrade kits (threshold).

- ***Environmental loads thresholds:*** 10 *psf* snow load, 80 *mph* sustained winds (up to 100 *mph* gusts), 205 *degree* Fahrenheit skin temperatures without permanent deformation, minimize ultraviolet degradation, and worldwide climate adaptation kits as necessary.

- ***Assembly/Disassembly cycles over a 20-year period:*** small and large shelter thresholds of 12 *cycles*; objectives are 26 *cycles* and 20 *cycles* for small and large shelters, respectively.

- ***Deployment length:*** 1-*year* threshold (2-*year* objective).

- ***Warehousing:*** at least five years with minimal inspection or maintenance (10-*year* objective).

- ***Shelf life:*** at least 20 *years*.

There are no specific thresholds or objectives for shelter weight, packing ratio, and cost (the three design attributes that conflict most severely with the new hardening requirements and objectives). Although we made preliminary recommendations for weight and packing ratio objectives in the working draft ORD submitted in December 1991, these recommendations are not included in the present draft ORD. To further explore the relative importance of these competing design attributes, we conducted a follow-up survey of the RWG in June 1992.

4. RWG Follow-up Survey

After the RWG meeting, we distributed a brief follow-up survey of the AF attendees of the portable shelter RWG meeting. We briefed the RWG on our preliminary research results and emphasized that the shelter design objectives must be prioritized to ensure the selection of the best possible shelter concepts. However, the primary goals of the portable shelter sessions of the RWG meeting were to present, review, and edit the working draft ORD developed under this task. As a result, there was not sufficient time to adequately address the issue of prioritizing the competing shelter design objectives. Hence, our primary purpose in conducting the RWG follow-up survey was to attempt to fill this gap by gathering some basic information on the relative importance attached to several of the major design goals. Twenty-one of the 40 AF RWG attendees completed and returned the survey. Although the sample populations was not scientifically selected, the respondents represent a fairly wide cross-section of the AF portable shelter community. A complete summary of the RWG survey results is presented in Appendix C.

Six major shelter objectives were addressed in the RWG survey: (1) transportability, (2) rapid assembly, (3) low cost, (4) functionality and operability, (5) reliability and maintainability, and (6) hardness. The overall opinion of the respondents was that none of these six objective is much more or much less important than any of the others. Weights assigned to the six categories ranged from 12 *percent* to 20 *percent* with functionality/operability and transportability weighted the heaviest and low cost and hardness weighted the least. The differences between the weights assigned for small and large shelters were statistically insignificant. Therefore, we have developed a combined set of weights. These weights are used in the evaluation of candidate shelter concepts in Section IV.

Since the RWG survey was by necessity brief and general, further interaction with AF decision makers is still needed to develop a consensus on the relative importance of these competing shelter objectives. Therefore, we recommend that a second portable shelter RWG meeting be convened early in the next phase of the FOPS research and development program.

SECTION II

SHELTER CONCEPT SYNTHESIS

A. INTRODUCTION

In this section, we synthesize candidate basic (*i.e.*, nonupgraded) shelter concepts for the new FOPS. The small and large shelter concepts considered herein have nominal usable floor areas of 600 $feet^2$ and 4800 $feet^2$, respectively. First, in Section B, we review existing military and commercial shelters to provide a basis for developing shelter concepts, defining shelter attributes, and evaluating the feasibility for meeting the thresholds and objectives stated in the FOPS SON. Based on this discussion, we divide the shelter system into three major shelter components in Section C: geometry, structural system, and cladding (*i.e.*, environmental barrier). From the three basic groups of subsystem alternatives and the overview of current and developmental shelters, we synthesize the small and large shelter concepts in Section D. The sixteen small shelter concepts and eight large shelter concepts are formally assessed in the shelter evaluation task in Section IV. Integral and upgraded hardening design alternatives for the basic shelter concepts are presented in Section III.

B. OVERVIEW OF CURRENT SHELTERS

Our review of current portable shelters concentrates on the characteristics (*i.e.*, structural system, geometry, materials, and cladding) and attributes (*e.g.*, erection rate and packing ratio) of the shelters according to the hierarchy shown in Figure 2. We have chosen the cladding system as the principal distinguishing feature of a shelter system. providing the following four major categories of shelters: (1) fabric shelters, (2) rigid-panel shelters, (3) built-up load-bearing wall shelters, and (4) portable shells. Within each class, we differentiate shelter concepts according to their structural systems (*e.g.*, pole-, frame-, edge-, and air beam-supported for fabric shelters and frame- and load-bearing panels for rigid-panel systems). Some categories shown in Figure 2 are not represented by existing shelters; however, these categories are considered during the concept synthesis in Section D. Although shelter geometry is often determined by operational needs and structural limitations, we have also conducted a preliminary trade study on optimal proportioning of typical shelter geometries with respect to weight minimization and survivability maximization. These results are presented in Appendix C.

1. Fabric Shelters

a. Pole-Supported

The simplest fabric shelters are pole-supported tents. The *Tentage Reference Manual* [NRDEC, 1989] and AFP 93-12 Volumes III and IV summarize pole-supported tentage currently in the military inventory. The Harvest Eagle family of shelters contains three pole-supported tents — the GP Medium and GP Large tents, and the M-1948 kitchen [AFP 93-12-

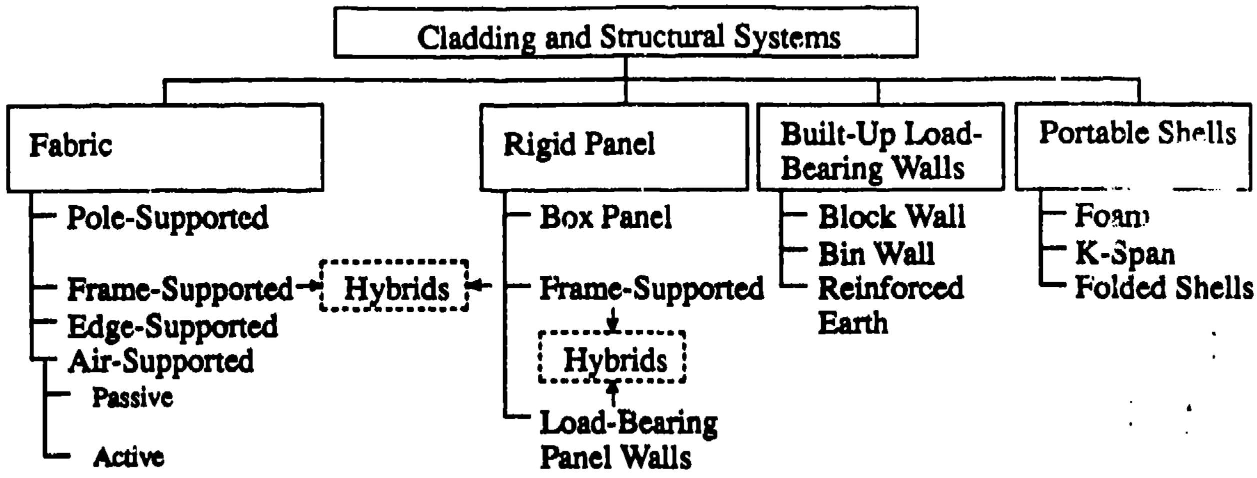


Figure 2. Hierarchy of Shelter Categories.

vIV]. The M-1948 kitchen has been replaced by the K-9 kitchen which consists of three interconnected TEMPERs (Tent, Extendible, Modular, Personnel), which are frame-supported. Pole-supported tents are generally inexpensive, highly transportable, and rapidly assembled. These features account for the extensive use of pole-supported tents by the U.S. Army [NRDEC, 1989]. For the longer term deployments typically encountered in bare base scenarios, pole-supported tents have several drawbacks such as internal obstructions, poor stability, regular maintenance (*e.g.*, upkeep of anchorage and fabric tension), and generally poor habitability. These drawbacks caused the Air Force to move away from the use of pole-supported tents during the development of the rigid-wall family of Harvest Bare shelters in the late 1960's and early 1970's.

The GP medium (GPM) is 16 *feet* × 32 *feet* (512 $feet^2$) and measures 5.5 *feet* high at the eaves and 10 *feet* high at the ridge. It weighs 569 *pounds* (including tent, liner, pins, and poles) and has a cube of 33 $feet^3$ (packing ratio of 120:1). The GPM erects in about 40 *minutes* with a crew of four (200 $feet^2/man\text{-}hour$) and provides billeting for 12 people.

The GP large (GPL) measures 18 *feet* × 52 *feet* (936 $feet^2$ of floor space) and is 12 *feet* at the ridge and 5.5 *feet* at the eaves. It weighs 820 *pounds* and packs into 69 $feet^3$ (packing ratio of 119:1). A crew of six can erect the GPL in approximately 1 *hour* and 15 *minutes* (125 $feet^2/man\text{-}hour$). When used for billeting, the GPM accommodates 22 people.

Both the GPM and GPL originally used a 9.5-*ounce* cotton duck fabric. A lighter weight polyester duck has replaced this fabric in recent purchases. The U.S. Army Natick Research, Development, and Engineering Center (NRDEC) is currently developing a new tent to replace the GP tents. The new tent, shown in Figure 3, is pole- and/or frame-supported, is intermediate to the GP and TEMPER in functionality and livability, corrects some of TEMPER's deficiencies, and uses recent material and rapid erection technology advances.

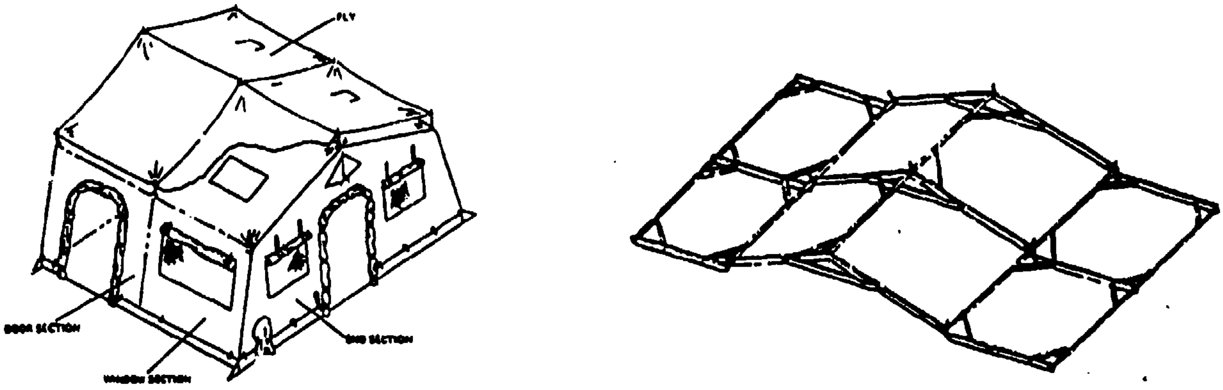
Figure 3. Prototype NRDEC New Technology Tent.

b. Frame-Supported

Lightweight, frame-supported fabric shelters are the most prevalent class of fabric shelters. Frame-supported tents alleviate most of the deficiencies noted above for pole-supported tents while imposing fairly modest increases in cost, packing volume, and weight. Numerous shelters of this type are available and we will not attempt to summarize all of these shelters. The NRDEC *Tentage Reference Manual* [1989] summarizes military frame-supported tentage while Brilhante and Saab [1989] survey commercially available large area frame-supported fabric shelters. The TEMPER is the centerpiece of the Air Force bare base deployment plan and is currently designated for approximately 90 *percent* of the shelter requirements on a typical bare base [AFP 93-12, vIII]. Large, commercially available shelters include the Seaman FSTFS (Frame-Supported, Tension Fabric Shelter), the Clamshelter, and the Fabric Building Systems (FBS) Vehicle Maintenance Shelter, which were procured and used by various military agencies in DESERT STORM.

(1) TEMPER

The TEMPER, shown in Figure 4, consists of a collapsible aluminum frame covered with a 13.5-*ounce* vinyl-coated polyester fabric. It is 20 *feet*, 6 *inches*



a. Fabric Shell   b. Frame (partially collapsed)

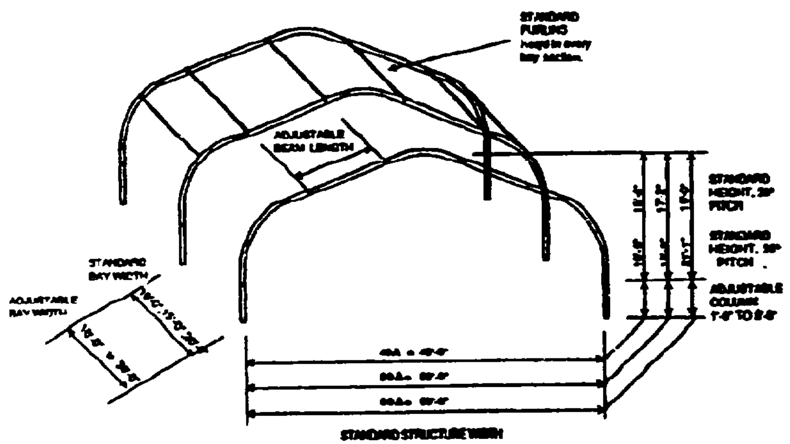
Figure 4. TEMPER Tent.

wide and is extendable in 8-*foot* sections to provide an unobstructed floor space of indefinite length. Each module can be configured using any combination of window or door sections. Modules can be complexed using vestibules to connect sides and ends. A tent fly reduces solar loading and provides additional environmental protection. An insulated, single-ply fabric floor provides temporary flooring. Quoted erection rates range from 80 *feet*^{2}*/man-hour* [AFP 93-12-vIII] to 160 *feet*^{2}*/man-hour* [AFP 93-12-vIV] and satisfy the ORD threshold erectability requirement of 75 *feet*^{2}*/man-hour*. The TEMPER is suitable for worldwide use in all climates. Special-use configurations are available for personnel billeting, utility, sanitation, kitchen, and medical use functions.

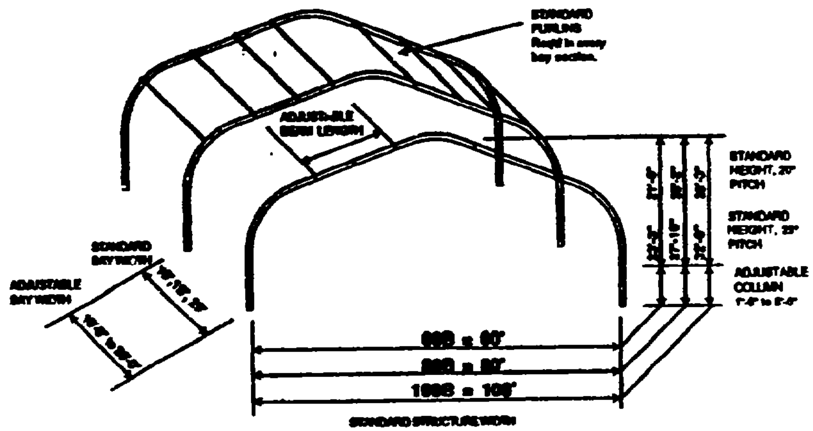
(2) Fabric Building Systems/Canvas Specialty.

FBS markets a family of frame-supported fabric structures under the trade names of FAST-STRUCTURE and FAST-TRUSS [FBS, 1992]. The shelters are manufactured under license by Canvas Specialty. The shelters feature modularity in the metal frame components and fabric panels, providing a wide range of potential spans and shelter lengths. They are ground erectable with hand tools at a rate of approximately 60 *feet*^{2}*/man-hour* (200 *feet*^{2}*/man-hour* for striking) and do not require a foundation. Adaptation kits are available for higher snow loads and high wind resistance.

The basic structural system employs transverse plane frames connected longitudinally by purlins, as illustrated in Figure 5. The FAST-STRUCTURE uses extruded aluminum box beams for spans of 40 to 60 *feet* (4 *inches* × 8 *inches*) and 60 to 100 *feet* (5 *inches* × 11 *inches*). Longer spans use the FAST-TRUSS system with span lengths ranging from 100 to 160 *feet*. The fabric membrane is 19-*ounce* vinyl-coated polyester (3.2-*ounce*) fabric, with optional fabric weights of 24, 28, and 32 *ounces*.



Fast Structure
Structure Profiles Type 40A, 50A, and 60A
Standard Dimensions and Adjustable Components



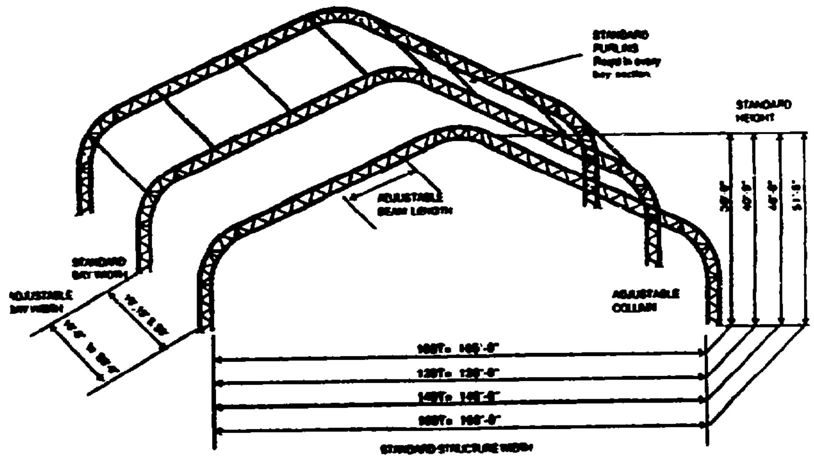
Fast Structure
Structure Profiles Type 60B, 80B, and 100B
Standard Dimensions and Adjustable Components

STANDARD FABRIC SPECIFICATION

A. Membrane Specification, 19 oz. fabric

1.	Base Weight	3.2 oz. per sq. yd.	
2.	Finish coated weight	19 oz. per sq. yd.(±2)	*Method 5041
3.	Tongue Tear	110 lbs.per in.	*Method 5134
4.	Trapezoid tear	35/40 lbs.	*Method 5136
5.	Grab Tensile	260/260 lbs.	*Method 5100
6.	Strip Tensile	200/200 lbs.per in.	*Method 5102
7.	Adhesion	10 lbs. per in.	*Method 5970
8.	Hydrostatic resistance	350 psi	*Method 5512
9.	Cold Crack	Pass -40° F	MIL-C-20696C
10.	Fire Resistance	2 seconds	*Method 5903
		(meets CA State Fire Marshall, UL 214, NFPA-701).	
11.	Color	White translucent or opaque	

* Federal Test Method Standard number 191.



Fast-Truss Structure
Structure Profiles Type 100T, 120T, 140T, and 160T
Standard Dimensions and Adjustable Components

Figure 5. Fast and Fast-Truss Structural Frame and Fabric Specification [FBS, 1992].

The U.S. Army purchased and deployed 56 FAST-STRUCTURES for use in Operation DESERT STORM as vehicle maintenance shelters. These shelters spanned 64 *feet* and were 122 *feet* long (tip to tip), as shown in Figure 6. The shelters were erected from the ground (no cranes or forklifts) by a crew of eight personnel in 14 *hours* (approximately 60 *feet*^{2} of usable floor space per *man-hour*).

(3) CBI Clamshelter

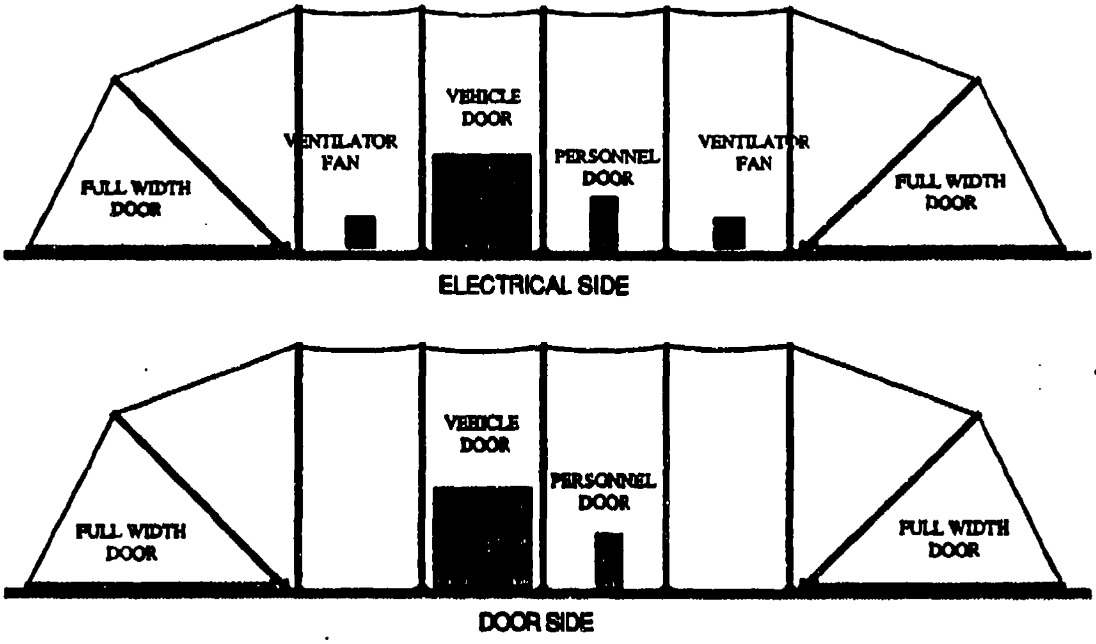
The Clamshell Buildings, Inc. (CBI) Clamshelter is a family of adaptable frame-supported fabric shelters composed of two basic series, the System 50 [CBI, NDa] and System 100 [CBI, NDb]. Both systems use a structural frame consisting of a series of transverse planar arches interconnected with purlins. The shelter frames are highly standardized and consist of four main components, with no component larger than 12.5 *feet* or heavier than 150 *pounds*. The arch frame consists of three standardized beam elements (two straight and one curved) of extruded 6061-T6 aluminum alloy as shown in Figure 7. The selection and number of the two straight beam sections are varied to customize the shelter's span and eaves' height. Beam lengths for the System 50 are nominally 7 and 11-*feet*, producing spans ranging from 28 to 74 *feet*. System 100 Clamshelters substitute aluminum trusses for the beams and provide spans of 94 to 200 *feet*. Fabric for both shelter systems is a Polyester/PVC laminate with weights ranging from 16 to 28 *ounces/yard*^{2}.

Like the FAST-STRUCTURES, the Clamshelters are erectable from the ground up. Figure 8 shows the Clamshelter erection sequence, which is similar to that for the FAST-STRUCTURE. Arches are assembled on the ground and attached to a base that is anchored to the ground. Arches are raised using a winch and purlins and shear cables installed. The fabric weather shell is then pulled through grooves in the arch components using leader cables. A typical 7,000-*foot*^{2} Clamshelter requires two days for installation by a four-man crew (109 *feet*^{2}/*man-hour*). With packing ratios as high as 600 to 1, a typical 15,000-*foot*^{2} System 50 Clamshelter can be stored in a single 20-*foot* ISO container, while the typical System 100 requires two 20-*foot* ISO containers.

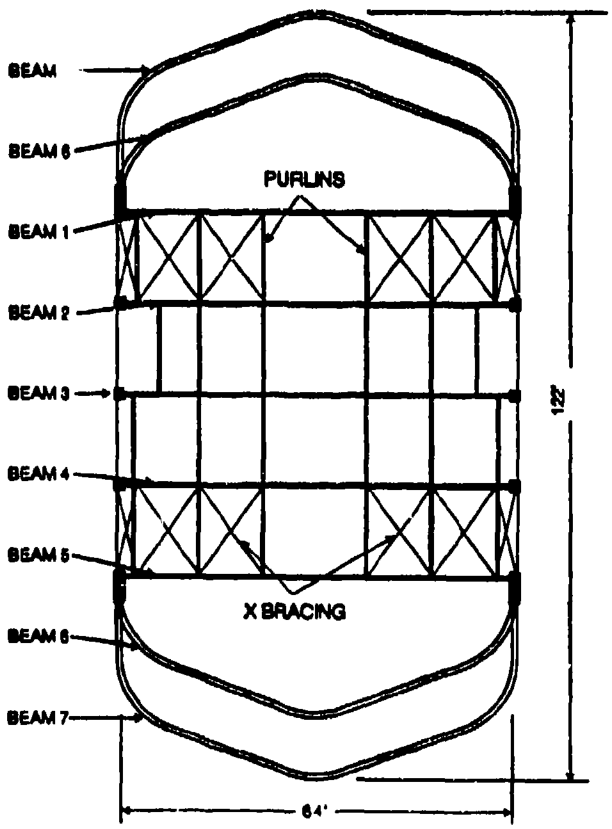
The Army Aviation Support Command purchased 144 System 50 Clamshelters for use in Desert Storm as helicopter maintenance shelters, and the Air Force is currently leasing eight System 50 Clamshelters to temporarily house F-117 Stealth fighters at Holloman Air Force Base.

(4) Seamen Corporation

Seaman manufactures two types of frame-supported fabric shelters, the Portomod and the FSTFS [Seaman, 1991a, b, c]. Both systems employ a series of parallel arch frames interconnected by purlins. The Portomod arch frames are constructed using hot dipped galvanized steel trusses (A36 steel) while the FSTFS uses extruded aluminum box beams (6061-T6). The fabric skin for both shelters is a vinyl-coated DuPont Dacron polyester fabric.



Structure Elevation



Plan View Structure

Figure 6. FAST-STRUCTURE DESERT STORM Vehicle Maintenance Shelter [FBS, 1992].

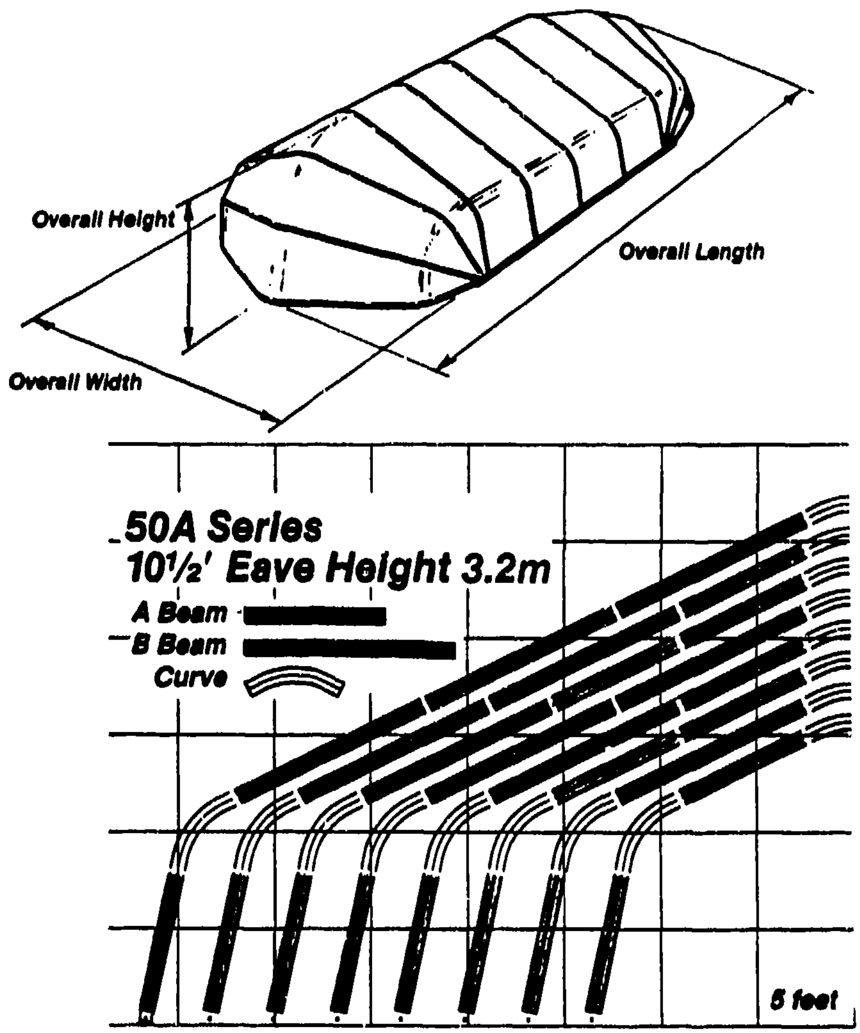


Figure 7. Clamshelter System 50 [CBI, NDa].

Portomod shelters, shown in Figure 9.a, come in three basic types (Type I, II, and III) depending on span (40 to 200 *feet*). The structural frame consists of a series of parallel cylindrical arch trusses with two diagonal arch trusses at each end. A flexible vinyl-coated polyester membrane is tensioned over the shelter frame using catenary cables located in pocket welds in the fabric membrane. Downward adjustment of the tensioning assembly tensions the fabric to the frame, forming engineered saddle shapes between arches. Assembly requires the use of a light crane to position the fabric bundle at the crest of the shelter where it is unfolded onto the shelter sides. In plan, the finished shelter resembles a split hexagon separated by a series of parallel bays. Twenty-six Portomod shelters were purchased and deployed in West Germany in 1980 to provide warehousing for prepositioned war reserve materiel (WRM). Equipment stored in these warehouses for several years was successfully deployed to Saudi Arabia as part of DESERT STORM.

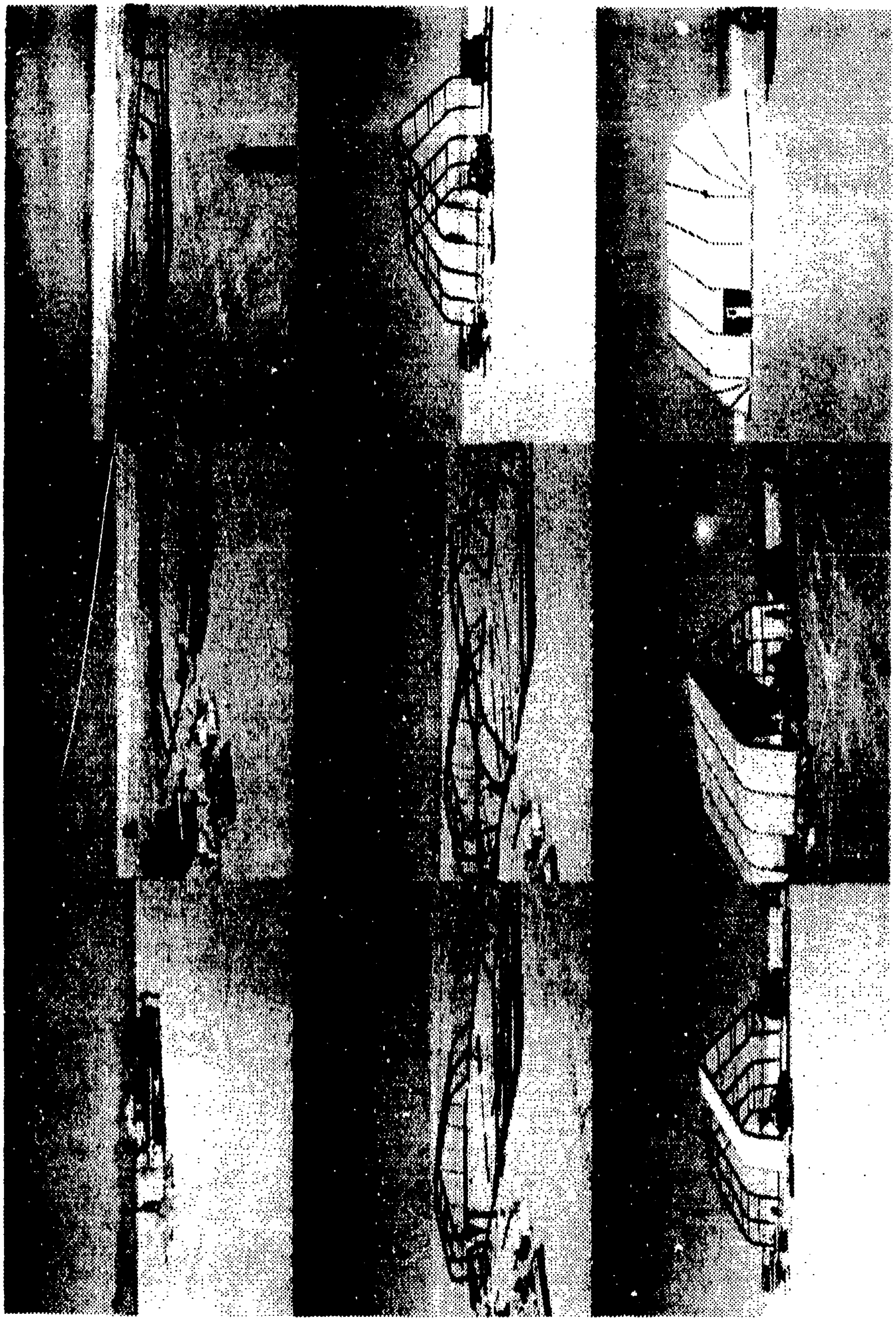
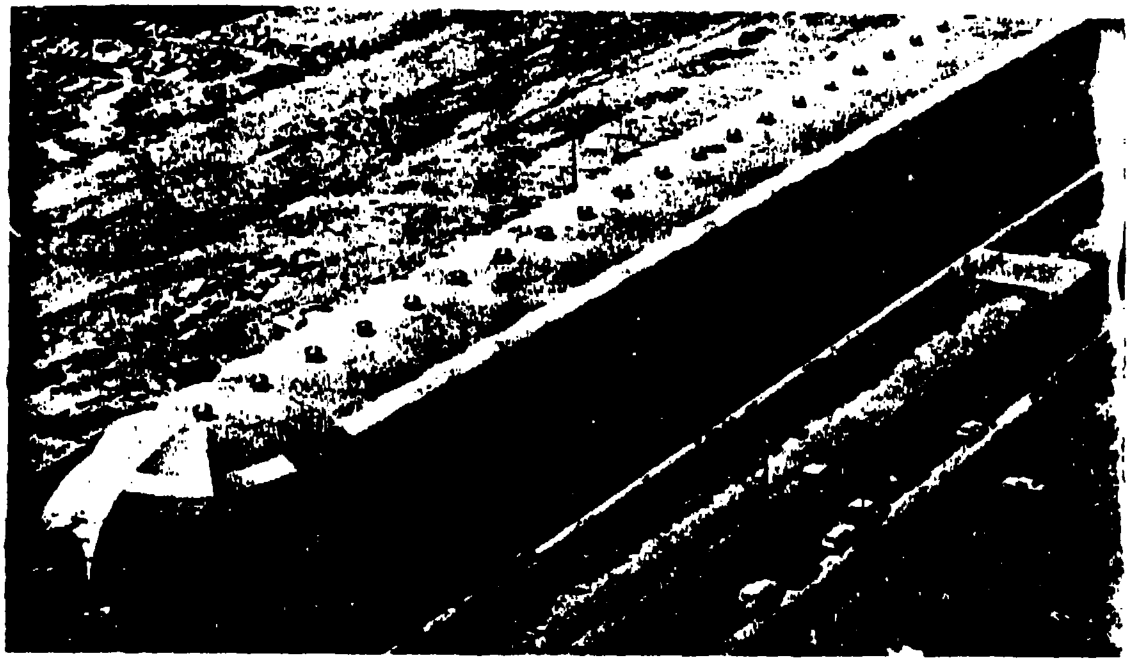
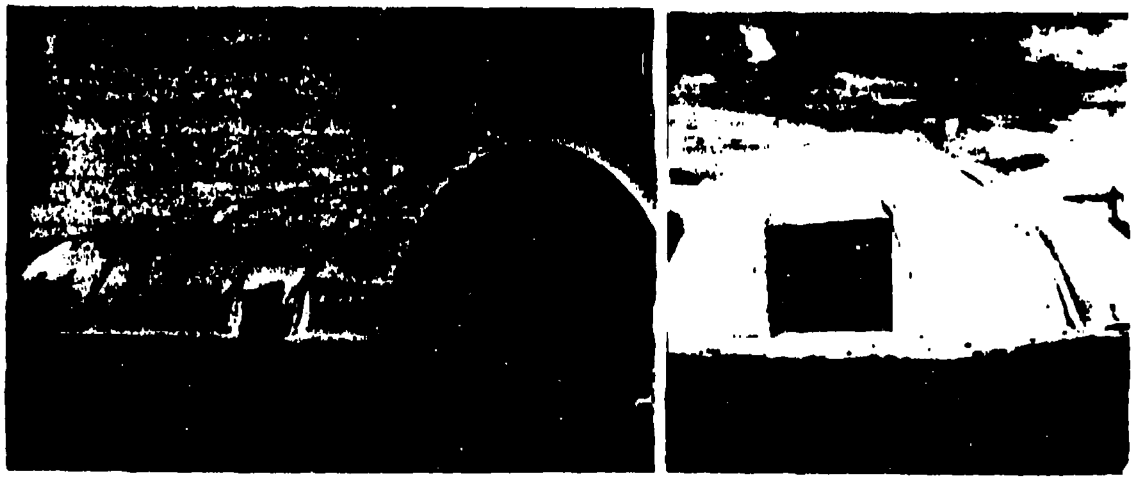


Figure 8. Clamshelter Erection Sequence [CBI, NDc].



a. Portomod Shelter



b. FSTFS Shelter

Figure 9. Seaman Corporation Portomod and FSTFS Fabric Shelters [Seaman, 1991}.

FSTFS shelters (Figure 9.b) are structurally similar to the FAST-STRUCTURE and Clamshelter in that they employ a series of transverse planar arches interconnected by purlins as their structural system; they are different in that the cross-sectional geometry is cylindrical. This cross-section provides an additional level of component standardization in that the structural frame has only three primary components: (1) arch beams, (2) arch beam connectors, and (3) purlins. Arch beams are box-sections with grooves for installing the fabric shell and liners. Beam segments are connected by splice sections bolted to one beam segment and pinned to the other.[1] Each arch section is assembled on the ground, attached to the base, and rotated vertically into place. The fabric skin (vinyl-coated DuPont Dacron polyester) is then fed into the grooves in the beam segments and pulled over the top. The Air Force purchased and deployed 106 FSTFS shelters as part of DESERT STORM.

c. Edge-Supported

A third option in the category of fabric shelters is an edge-supported or stressed membrane fabric roof shelter. In this concept, roof loads are carried by fabric membrane forces to either a compression ring or a set of cables that carry the tensile forces over an edge support and into ground anchors. In order to maintain tension in an edge-supported fabric under all anticipated loading conditions, the roof must be negatively curved (see Section II.C.2). Since the edge supports are generally framed or arched elements, the edge-supported fabric roof shelter can be thought of as a special case of frame-supported fabric shelters. However, because the fabric roof acts as a membrane and is a significant element in the primary structural system, we have chosen to consider edge-supported fabric shelters as a separate concept class. We were not able to identify any current portable shelters that fall into this shelter class.

d. Air-Supported

The structural frame in a frame-supported fabric shelter occupies a significant fraction of the shipping volume, and its erection constitutes a major portion of the shelter erection time. Air-supported shelters eliminate the need for a separate structural support system by using pressurized air to support the fabric skin. The air-support system may be either passive or active. In passive air-supported shelters, the interior environment is kept at normal atmospheric pressure — air pressure is passively maintained in sealed bladders. The interiors of active air-supported shelters, on the other hand, are moderately pressurized. The internal pressure must be constantly maintained by mechanical blowers. Erection of air-supported shelters only requires laying out and anchoring the shelter fabric, and supplying a pressurized air source to inflate the shelter. Consequently, air-supported fabric shelters offer the greatest potential for improving mobility in terms of transportability (packing efficiency) and erection speed.

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[1] Erection tolerances may potentially be a problem with this type of connection. A tour of a FSTFS shelter erected at Shaw Air Force Base revealed some instances where one of the two pins inserted into beam connections was loose, indicating that all the load was being transferred through one pin. Since the shelters are to be erectable using warskill labor, a design modification may be necessary to ensure proper load distribution in the connection.

(1) Passive Air-Supported

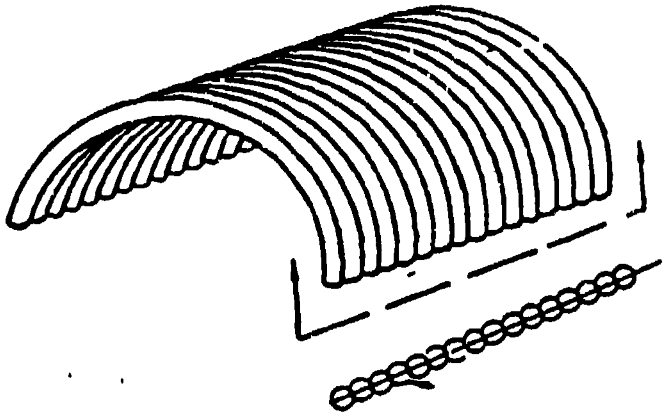
Figure 10 illustrates some examples of passive air-supported shelters. In these shelters, the air pressure is maintained in either pressurized ribs/beams (discrete parallel or tilted arches) or in the cavity created by a dual-wall system (contiguous arches). The structural difference between discrete air beam shelters and dual-wall shelters is analogous to the difference between arches and cylindrical shells. That is, the air beam shelter concentrates its load carrying capacity into several individual elements while the dual-wall shelter essentially provides continuous load resistance (typically, dual-wall inflatables are divided into adjacent cells to prevent the propagation of pressure losses).

Dual wall shelters are in the inventory of standard and developmental Army tents [NRDEC, 1989] and have been studied in the past as an Air Force hangar concept. Examples of this type of construction are the M51 collective protection chemical/biological shelter and the air-inflatable, double-wall, combat support hospital. Erection rates for these shelters are 67 and 123 *feet²/man-hour*, respectively. These erection rates are comparable to those for frame-supported systems and do not justify the incremental costs, added maintenance, and shorter life expectancy. The combat support hospital shelter has not been procured in over 7 *years* and has been replaced by the TEMPER.

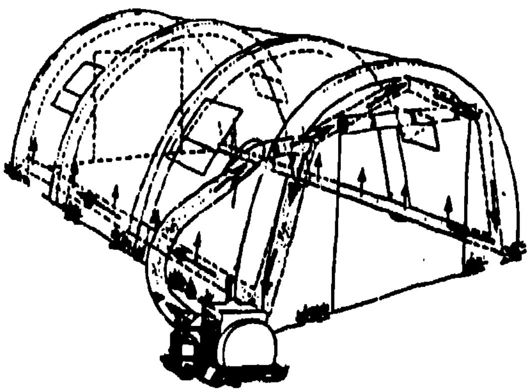
The TrellTent [Trelleborg, ND], shown in Figure 10.b, is an air beam-supported fabric shelter developed for the Swedish Armed Forces to house field hospital units. The structural system consists of four parallel cylindrical air-arches (pressurized to 2.6 *psi*) with aluminum alloy purlins between the ribs to provide stability. The TrellTent provides 407 *feet²* of floor space and can be erected by two people in 10 *minutes* (1220 *feet²/man-hour*) with the aid of a low-pressure fan unit. Packing volume is less than 35 *feet³*. The floor is sewn and welded to the walls to provide waterproof and dust-tight joints. Collective protection can be incorporated with additional sealing.

The Chemically and Biologically Protected Shelter is a tilted-arch airbeam-supported fabric shelter currently under development by Natick and scheduled to replace the M51 shelter. The shelter consists of a Teflon®-coated Kevlar® fabric shell supported by neoprene coated nylon tubes pressurized to 2.5 *psi*. The shelter provides 350 *feet²* of C/B protected space, is operational between -25 and 120 *degrees* F, and weighs a total of 650 *pounds* (including shelter, insulation, airlocks, doors, lights, and miscellaneous support equipment). This shelter will operate as a Battalion Aid Station enabling a crew of four to perform emergency medical treatment and move up to three times a day. NRDEC has also investigated tilted arch air beam construction for use as a transportable helicopter enclosure (THE) [Rinehart and Oliver, 1983] and as a possible replacement for the TEMPER.

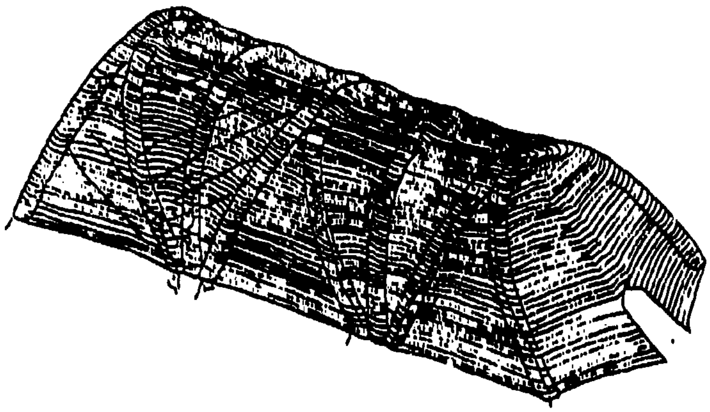
Because no rigid structural elements or rigid cladding elements are required, air-inflated shelters generally offer exceptional mobility and low cost. The main drawbacks of air-inflated shelters are: the need for pressurized air during assembly, reduced load



a. Contiguous Parallel Arch



b. Parallel Arch (TrellTent)



c. Tilted Arch Construction (Transportable Helicopter Enclosure)

Figure 10. Air Beam-Supported Fabric Shelters.

capacity and stability in comparison to frame-supported shelters, vulnerability to loss of pressure, and poor to fair habitability. Additionally, air pressure dependency on temperature can result in loss of inflation and instability of the shelter. Thus, the air-inflated shelter concepts offer clear tradeoffs.

(2) Active Air-Supported

The entire fabric of active air-supported shelters serves as both the cladding system and the structural system. Active air-supported shelters are generally positively curved membrane structures (see Section II.C). The fabric is stressed into tension by a continuous interior overpressure that is maintained by mechanical blowers. Because the entire membrane is prestressed, the required interior overpressures are on the order of the maximum expected roof loads (*e.g.*, 10 to 40 *psf* snow loads).

The Transportable Collective Protection System (TCPS) Contamination Control Area (CCA), under development at NRDEC, is an example of an active air-supported shelter [NRDEC, 1989]. CB protection is an ideal application for air-supported shelters since the internal overpressure serves the dual purposes of structural support and prevention of CB infiltration. Active air-supported shelters have many of the features and drawbacks of passive air-inflated shelters; however, the need for continuous pressurization is a drawback not found in air-inflated shelters. Thus, the active air-supported fabric shelter concept may be best suited to CB environments where there is a non-structural need for internal overpressure.

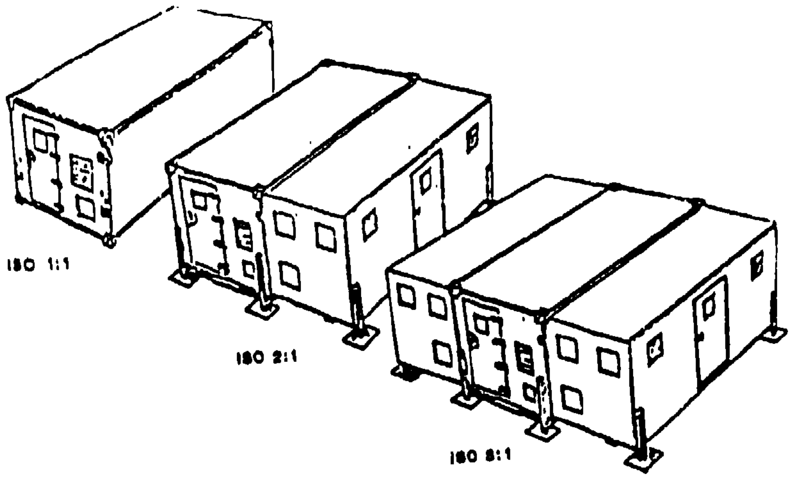
2. Rigid-Panel Shelters

There are two major classes of current rigid-panel shelters: AF Harvest Bare shelters and DOD tactical shelters. The Harvest Bare family of shelters includes four rigid panel shelters: (1) the Expandable Shelter/Container (ESC), (2) the Expandable Personnel Shelter (EXP), (3) the General-Purpose (GP) Shelter, and (4) the Aircraft Maintenance Hangar (ACH). These shelters were developed in the late 1960s and have been in use since that time. The features of the four Harvest Bare rigid-panel shelters are summarized in the following subsections. Additional information can be found in [AFP 93-12-vII, ND] and [AFP 93-12-vIV, ND].

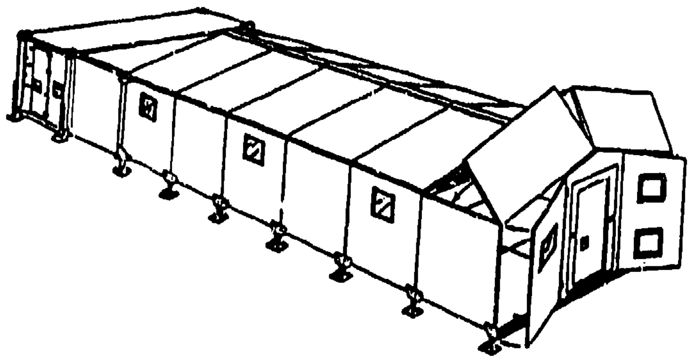
Tactical shelters are a family of thirteen portable expandable and nonexpandable unitized shelters that, to the extent practical, are designed according to ISO (International Organization for Standardization) specifications for land, sea, or air transport. ISO requires standard corner fittings and structural container design details that facilitate handling and provide compatibility with commercial and military truck, rail, container ship, helicopter, and aircraft transportation systems. The tactical shelter family includes standard and specialized versions of the $8 \times 8 \times 20$-*foot* ISO (nonexpandable, one- and two-side expandable); smaller units such as the S-250, S-280, and S-530 shelters; Marine Corps knockdown shelter; ISO Army Accordion shelter; MERWS (Modular Extendible Rigid Wall Shelter); and several complexing and integration units. The shelters are complete units and require no specialized set-up equipment and minimal site preparation. Figure 11 illustrates several tactical shelters.

a. Box Panel Shelters

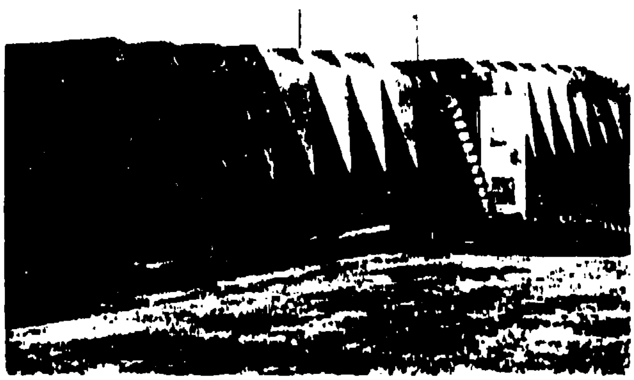
Box panel shelters are box-shaped, cellular structures that are either partially or fully assembled prior to transport. They are among the most common type of small, portable shelter and make up a large portion of the DOD standard family of tactical shelters. It is useful to further classify box shelters according to their expansion ratio (*i.e.*, the ratio of expanded volume to shipping volume) as non-expandable, expandable, and highly expandable.



a. ISO



b. MERWS



c. ISO Army Accordion Shelter

Figure 11. Tactical Shelters.

Nonexpandable box shelters are shipped fully assembled in their final configuration. There are seven nonexpandable DOD tactical shelters [NRDEC, 1989b]. Most of these shelters satisfy ISO (International Organization for Standardization) shipping container requirements. There are no nonexpandable, general-purpose shelters in the current inventory of AF bare base shelters. Nonexpandable shelters are generally limited in size and create an unacceptably large airlift demand for typical bare base applications.

Expandable box shelters are defined herein as partially assembled box shelters that have nominal expansion ratios of 2:1 or 3:1. The ratios correspond to one-sided expandables and two-sided expandables, respectively. Three tactical shelters and at least one bare base shelter fall into the expandable box shelter category. The Harvest Bare expandable shelter/container (ESC) is a two-sided expandable shelter used for flight line and industrial shops, latrines, and kitchens. The ESC unfolds from a packaged center structure (8 *feet* × 8 *feet* × 13.3 *feet*) to provide a shelter measuring 8 *feet* × 21.4 *feet* × 13.3 *feet* (285 *feet*^{2} floor area with a packing ratio of 2.6:1). The ESC is constructed of aluminum/honeycomb sandwich panels with structural framing and windows of cast and extruded aluminum. The ESC can be erected by a crew of four to six people in 2 *hours* (24 to 36 *feet*^{2}*/man-hour*). As with non-expandables, expandable box shelters are generally too small and too bulky for the general-purpose applications considered in this study.

Box shelters having nominal expansion ratios greater than 3:1 are classified as highly expandable box shelters. The only current and/or developmental examples of highly expandable box shelters are the Harvest Bare expandable personnel shelter (EXP) and the ISO Army 50-*foot* Accordion (the tactical shelter program analog to the EXP) which have nominal expansion ratios of 12:1 and 6:1, respectively. These shelters have box-shaped cores in which folded panels are stored during transport. The panels are unfolded in accordion fashion to form the walls and roof in the final configuration. The EXP's walls, ceiling, and floor are aluminum/honeycomb sandwich panels, and its expanded walls and ceiling are accordion-pleated foam board panels. When expanded, the EXP measures 13.6 *feet* wide, 8.2 *feet* high, and 32 *feet* long (435 *feet*^{2}). A crew of four to six can erect the EXP in 2 *hours* (36 to 54 *feet*^{2}*/man-hour*) [AFP 93-12-vIII]. The ISO Army Accordion (Figure 11.c) packs in the standard ISO configuration (8 × 8 × 20-*foot*), measures 7.08 *feet* high × 49 *feet* wide × 19 *feet* long (interior) when expanded (931 *feet*^{2}), and has a target erection rate of 4 *hours* by a crew of four (58 *feet*^{2}*/man-hour*) [NRDEC, 1989b].

b. Frame-Supported Panel Shelters.

Frame-supported panel shelters are typically highly expandable (*e.g.*, from about 10:1 up to 40:1) rigid wall shelters that are shipped in many disassembled pieces. In addition to traditional frames, this class also includes other related structural systems such as arches and trusses. We shall refer to all such panel shelters as frame-supported panel shelters. In these shelters, the cladding system plays either a secondary or negligible role in the overall structural behavior of the shelter. Providing out-of-plane bracing for parallel frames is a typical secondary structural role for the panels in a frame-supported panel shelter.

The advantages of frame-supported panel shelters generally include strength, stability, maintainability, and habitability. Drawbacks include cost and rapid assembly. Transportability generally falls between the two extremes of fabric shelters and box-panel shelters. Current examples of frame-supported panel shelters include the Harvest Bare GP and ACH shelters.

GP Shelter. The general purpose (GP) shelter pictured in Figure 12 is a medium sized shelter used as a dining hall, meeting facility, maintenance shelter, or warehouse. Shelter dimensions are approximately 31 *feet* × 48 *feet* × 12 *feet*. The structural system is a series of segmented arch sections constructed of rigid honeycomb panels and I-beams. Six panels and twelve I-beams make up each arch section, which is self-supporting and erected independently. Adjacent arches are connected using adjustable braces and covered with a vinyl-coated fabric flashing. Access is through personnel or vehicle doors provided on opposite endwalls of the shelter. A crew of six can erect the GP shelter on a prepared surface in 15 to 20 *hours* (12 to 16 *feet²/man-hour*). The GP shelter packs into an 8 × 8 × 10-*foot* container.

ACH. The 76-*foot* aircraft maintenance hangar (ACH) is used for aircraft and vehicle maintenance, weapons loading, and similar functions. It is structurally similar to the GP shelter, consisting of a series of free-standing arch sections constructed of aluminum/honeycomb rigid panels and aluminum I-beams. The beams and panels are locked together on the ground, double-pinned together at the beam ends, and progressively hoisted using an A-frame hoist to form an arch section. Adjacent arch sections are joined using adjustable braces and covered with fabric flashing. Fabric clam-shaped end closures provide full-width doors for aircraft access. When erected with the doors closed, the ACH provides a shelter 76 *feet* wide, 125.5 *feet* long, and 25 *feet* high at the crest. It packs into four shipping containers measuring 8 × 8 × 10 *feet* which are used as vestibule-like entries for personnel. The ACH is erectable by a crew of twelve in 10 to 12 *hours* (67 to 80 *feet²/man-hour*) [AFP 93-12-vIII].

c. Hybrid Panel/Frame Shelters

This category of rigid-wall shelters is a cross between frame-supported and box panel shelters. In hybrid panel/frame shelters, there is not a complete frame, truss, or arch system. Instead, some of the panels are an integral part of the structural system while the remaining panels are primarily for cladding purposes. The combined use of frames and shear walls in the construction of many permanent buildings is analogous to the concept of portable hybrid panel/frame shelters.

The MERWS, shown in Figure 11.b, is an example of a hybrid panel/frame shelter. The shelter is designed to ship in and expand off of the side of a one- or two-sided expandable ISO container. The MERWS wall panels are load bearing, providing structural support

Figure 12. Bare Base GP Shelter.

for the roof structure and lateral bracing against wind loads. The roof is supported by lightweight aluminum trusses while the floor is supported by a system of beams and girders. Therefore, the floor and roof panels in the MERWS play secondary structural roles.

MERWS has been recently redesigned by DBA Systems, Inc., under contract to NRDEC. Lighter materials have been incorporated; quick connect/disconnect systems have been developed for the jacks, floor beams, and roof trusses; and leveling has been facilitated. The improved setup times are comparable to those for frame-supported fabric shelters. DBA Systems is investigating alternative panel designs to reduce weight, increase structural strength and stiffness, and enhance thermal resistance. The new panels replace the aluminum skins with fiberglass reinforced plastic skins (Kemlite) and use Divinycell foam and Trevira matting (a fibrous material) as the core material instead of phenolic impregnated kraft honeycomb. The resulting panels are 20 *percent* lighter and have an increased R value. Relative cost and performance data for the new panels are not yet available.

The MERWS system is promising for FOPS in that: (1) it meets erection requirements of 75 *feet*^{2}/*man-hour* (3- to 4-*hour* setup by a four-man crew), (2) it provides 1080 *feet*^{2} of unobstructed floor space when erected, (3) offers potential for sustained deployment for long periods, and (4) can be reengineered to conform to 463L airlift pallet and materiel handling systems. Ballistic hardening can be incorporated as an intrinsic property of the composite panels, or can be field installed as an appliqué. However, the downside of the MERWS concept is its relatively poor packing ratio (6.8:1) as compared to fabric shelters. Hybrid designs incorporating rigid wall panels and a fabric roof can also be developed. The shelter can also provide protection from C/B agents through the use of an overpressure system and seals at all joints.

3. Built-Up Load-Bearing Wall Shelters

All of the shelters in this class have field constructed load bearing wall systems that function as both cladding and as primary structural elements. The three specific types of built-up load bearing wall shelters discussed below have the capacity to directly incorporate soil hardening upgrades directly into the wall during construction. None of the three systems is a standard portable shelter design.

a. Block Wall Shelter

The block wall shelter concept is patterned after conventional masonry construction, but the building blocks for this portable shelter concept would be manufactured on-site from lightweight, transportable raw materials. Candidate materials include plastics or lightweight foams. To stabilize the walls, the blocks would either be interlocking or reinforced. To minimize the use of raw materials, the blocks would have hollow cores. These voids would be filled in with soil during the construction of the shelter to provide integral protection against small arms and fragmenting weapon threats. A lightweight roofing system such as a truss-supported fabric roof would enclose the structure. A block wall shelter would be fairly inexpensive, provide better than average habitability (if it is properly constructed), and allow for integral soil hardening upgrades. The drawbacks of this concept include: the need for field manufacturing equipment, slow assembly, higher than average construction skill requirements, and only partial reusability of the shelter.

b. Bin Wall Shelter

The bin wall shelter concept starts with a conventional soil bin hardening system [Sues, *et al.*, 1991; Army FM 5-103, 1985], and incorporates it directly into the basic shelter design. The end effect is quite similar to the block wall shelter concept described in the previous paragraph except that the need for field manufacturing is eliminated and the shelter is 100 *percent* redeployable. Packing efficiency, on the other hand, is probably reduced since the bin wall materials will be transported to the site.

c. Reinforced Earth Shelter

The final concept under the category of built-up, load bearing wall shelters is the reinforced earth command, control, and communications (C3) shelter [Reid, 1991]. This concept is a highly protective shelter design that may be necessary for some portable C3 facilities and other high value assets. The reinforced earth concept utilizes panels that are tied back into a soil berm by a grid of reinforcing fibers. The wall, soil, and reinforcing system is built up and compacted one layer at a time to produce a bermed, box-shaped shelter. A simply-supported truss and panel roof system is used to enclose the structure. The roof system is intended to carry a two to three-*foot* soil overburden to provide overhead protection. As with the other built-up load bearing wall concepts, the main deficiencies of the reinforced earth C3 shelter are relatively slow assembly time, higher than average construction skill requirements, and the need for soil and earth moving equipment to construct the shelter. If carefully disassembled, the shelter should be essentially 100 *percent* reusable.

4. Portable Shell Structures

There are at least three current lightweight shell concepts that merit consideration as candidate portable shelter systems: (1) foam arches and domes, (2) the K-Span corrugated cylindrical shell system, and (3) hyperbolic paraboloid (hypar) folded shell structures. The first and second of these shelter concepts require some level of manufacturing in the field and, as a result, have serious drawbacks with respect to shelter redeployment. However, it is possible that the cost of these two shelter systems may be sufficiently low to make them feasible alternatives. Since non-redeployable design concepts are not specifically precluded in the current draft of the New Family of Portable Shelters ORD, we have elected to include foam dome and K-Span type shelters in our review and assessment of shelter alternatives. The third concept in this category, the hypar folded shell structure, is fully redeployable. In fact, the hypar shelter could be considered with the rigid panel concepts in Section B.2. However, since its structural behavior is fundamentally different and its panels are not flat, we have categorized the hypar concept in the portable shell group.

a. Foam Arches and Domes

The U.S. Army has developed rapidly erectable polyurethane foam structures for use in building Theater of Operations (TO) bases [Williamson, *et al.*, 1977; Smith, 1977, 1978, and 1983]. The shelters are constructed by spraying foam onto an inflatable hemispherical form. Foam material for these shelters is shipped in a dense form (approximately 70 *pounds/foot*^{3}) and foamed to a very low-density (1 to 2 *pounds/foot*^{3}) structural material. Although its low strength prohibits its use in many structural applications, its high strength-to-weight ratio permits its use in structural applications where externally applied forces are small and well distributed or where the structural geometry reduces the moments and stresses, such as arches and domes. The advantages of foam shelters include low initial cost, high packing ratios, and above average habitability. The drawbacks of foam construction include relatively slow assembly and the inability to redeploy a completed shelter.

The construction procedure for foam arches and domes is well developed, and the U.S. Army has built several arches and domes worldwide, including Germany, Panama, Egypt, Saudi Arabia, and stateside at several locations. Some of these structures have been standing for over 10 *years*. Several 24-*foot* wide × 60-*foot* long cylindrical arches and 36-*foot* diameter hemispherical domes were constructed by army personnel during deployment for DESERT STORM. These shelters were used for electronic equipment calibration, as a clean room for helicopter maintenance, and as mortuaries. A typical foam arch shelter required 14 *hours* for construction by a crew of three people (34.3 *feet*^{2}/*man-hour*).

The foam components and equipment required for shelter construction are commercially available in large quantities. The foam components are stable and dense in their liquid shipping and storage conditions and are easily expanded on-site using simple equipment. The formwork for erecting and shaping the foam is an air-inflated membrane that occupies little volume during shipping and is strippable and reusable. Labor intensity is moderate, requiring a three- or four-man team to operate the equipment and coordinate construction. Labor skill levels are also moderate: paint spraying skills are easily augmented by a brief training period to allow foam spraying. Site preparation is minimal, requiring only site leveling, floor construction, and ground anchoring to prevent the foam shelter from being lifted by the wind. Earth backfill around the sides of the structure can be applied to enhance stability and survivability against weapon effects. Durability, fire/flame spread resistance, and camouflage can be enhanced by adding fire retardant agents, painting, and applying cementitious coatings.

Foamed polyurethane construction has two other important functional capabilities. Properly applied, foam provides outstanding thermal and sound insulation. It provides sound insulation mainly by rigidizing panel components in buildings, reducing their ability to retransmit vibrations. Foam is also an excellent thermal insulator. A 36-*foot* foam dome has an R-factor of 40 and can be heated to a constant 72 *degrees* Fahrenheit in 24 *hours* using a 1500-*Watt* radiant heater (outside temperature below freezing).

b. K-Span Corrugated Cylindrical Shell.

Although field constructed corrugated cylindrical shells are considered semi-permanent shelters, the K-Span portable manufacturing system provides a low-cost and rapidly assembled shelter alternative. The K-Span system takes rolled sheet metal and deforms it on-site into a series of circular corrugated sections. The term cylindrical shell is somewhat of a misnomer since the true structural behavior is better described as a continuous series of parallel arches. However, since the cladding and structural system are fully integrated into a cylindrical geometry, we have chosen to consider this concept as a portable shell structure.

The structural shell is constructed in 1-*foot* continuous channel arch panels cold formed from 24-*inch* wide galvanized sheet steel (24-*gauge* (0.023-*inch*) to 19-*gauge* (0.04-*inch*)). The sheet steel is fed continuously into the K-Span roll-forming machine, which cold works the material into a straight channel section and cuts it to the desired length. The channel is then fed into the second stage of the forming machine that curves it to the desired radius. Arch panels are seamed together by crimping one top flange around another to form the cylindrical arch shelter with the desired length. Straight channel sections are used to form the vertical end walls.

The K-Span building system has many characteristics that are beneficial to rapid deployment. Field tests have shown that it can be erected easily and quickly, albeit at a rate of approximately 34 *feet*^{2}/*man-hour*, which does not meet the target 75 *feet*^{2}/*man-hour*. Most skills involved are simple and repetitive. With the majority of the structural components fabricated on-site, shipping volume and weight are low. Structural integrity of the system is sound and potentially can be strengthened to support soil dead loads for hardening against conventional weapon effects. The disadvantages are: (1) the system does not meet the 75 *feet*^{2}/*man-hour* construction rate, (2) the need for specialized forming equipment, (3) the need for specialized equipment for construction (crane or high mast forklift to lift arch sections into place, manlift or cherry picker for end-wall construction, and a welder and cutting torch), (4) construction skills requirements, and (5) difficulty in recovering or relocating.

Twenty-nine K-Span shelters were constructed by Red Horse construction personnel during the DESERT SHIELD/STORM [Caywood, *et al.*, 1991; TAC, 1991]. Table 2 summarizes cost and erection data for several of these shelters. The variability in cost and erection rate data is quite broad due to differences in peripheral construction requirements, crew experience, length of the work day (some entries are for 10 to 12-*hour* workdays), and equipment availability. Costs (including material and labor) ranged from \$5.38 to \$18.00 per *foot*^{2}. Erection rates were very low, due to material and equipment shortages. In short, the DESERT STORM performance was not up to levels observed in previous field tests.

c. Hypar Folded Shell Structure.

A lightweight, composite panel version of the hyperbolic paraboloid HUTCH shelter system described by Moriarty, *et al.* [1989] represents another viable portable shell concept. The constraints of air transportability may limit the maximum size of the hypar shelter, and expedient connection systems would be required for rapid assembly in the field. However, the folded hypar shelter appears to offer above average habitability, and its inherent strength and stability make it suitable for expedient protection methods such as mounding or berming. Furthermore, in spite of its complex three-dimensional geometry, the issue of modularity has been addressed by Moriarity, *et al.* [1989].

5. Current Portable Shelter Design Attributes

Mobility and cost data for many of the current or developmental portable shelters are tabulated in this subsection. The specific design attributes considered herein are packing ratio, weight ratio, assembly rate, and initial unit cost.[1] These four attributes are functions of six shelter characteristics: packed volume, expanded usable volume, shipping weight, usable floor area, assembly man-hours, and total first cost.

The data are divided into three groups. The first group is comprised of shelters listed in the *Bare Base Planning Guide* [AFP 93-12, ND], shelters listed in the *Standard Family of Tactical Shelters* [NRDEC, 1991], and two field manufactured shelters evaluated by the Army Civil Engineering Research Lab [Smith, 1977; Sweeney, *et al.*, 1991]. The second group is made

[1]Detailed definitions of the shelter design attributes are given in Section IV.C.2.

TABLE 2. DESERT STORM K-SPAN CONSTRUCTION DATA.

Project	Date	K-Span Dimensions (*feet*)	Floor Area (*feet*^{2})	Crew Size	Cost (*\$/feet*^{2})	Erection Rate (*feet2/MD*)	Comments
Al Kharj	12 Dec 90 - 1 Feb 91	3 - 50 × 100 3 - 50 × 80	5000 4000	36	16.25	17.8	Includes concrete floors
Al Jubail Maint. Shelters	7 Dec 90 - 24 Dec 90	2 - 64 × 80 1 - 64 × 100	5120 6400	13	7.49	75.3[a]	Trained Navy Seabees
Eskan Postal Support	22 Feb 91 - 7 Mar 91	1 - 60 × 100	6000	28	12.17	15.3	Rollup door, existing slab
Riyadh Comm. Storage/Maint.	6 Feb 91 - 15 Mar 91	1 - 50 × 100	5000	24	18.00	11.9	Insulation, gravel lot, security fence
Riyadh MEDIVAC Maint. Fac.	10 Feb 91 - 25 Mar 91	1 - 60 × 120	7200	28	8.33	6.0	Connecting road and concrete floor
Al Kharj Munitions Storage	4 Dec 90 - 12 Dec 90	4 - 50 × 50 1 - 50 × 100	2500 5000	29	5.38	51.7	Open bay
Al Kharj Aircraft and Vehicle Maint.	12 Dec 90 - 5 Jan 91	1 - 50 × 80 1 - 50 × 100 1 - 60 × 80	4000 5000 4800	28	6.30	29.0	Enclosed with Slab Foundation

[a] Does not include Navy Seabee personnel.

up of existing and developmental shelters listed the *Air Mobility Catalog* [Air Force Engineering Center, c. 1975]. The final group consists of standard and developmental shelters listed in the *Tentage Reference Manual* [NRDEC, 1989]. We were unable to obtain complete data sets for the second and third groups; therefore, the primary focus of this section is on the bare base, tactical, and field manufactured group of shelters.

a. Bare Base, Tactical, and Field Manufactured Shelter Attributes

We have compiled a relatively complete set of mobility and cost data for this group of 14 shelters. The shelter attributes are listed in Table 3. In a few instances, we have made estimations or projections to fill in missing data. These attributes are identified by italics. The first three shelters are frame, pole, and air beam supported fabric shelters, respectively. The last two entries are field manufactured portable shell structures, and the remaining entries are rigid panel shelters.

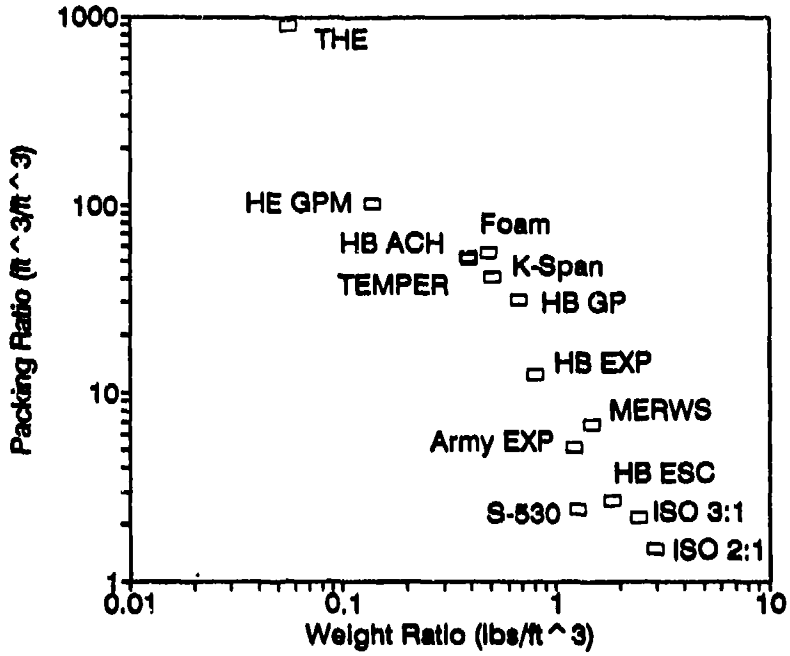
The four design attributes tabulated in columns two through five of Table 3 are plotted in Figure 13. Note that these graphs are log-log plots due to the large variabilities of the attributes.

Figure 13.a illustrates that there is a strong correlation between packing ratio and weight ratio (the two transportability design attributes). In general, the fabric shelters are in

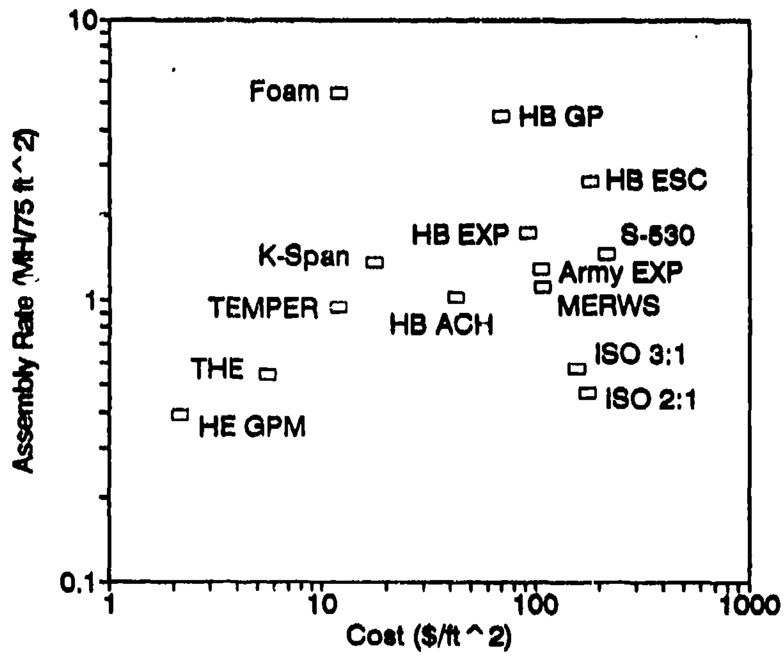
TABLE 3. BARE BASE, TACTICAL, AND FIELD-MANUFACTURED SHELTER DATA.

Shelter	Packing Ratio	lbs/ cu ft	MH/75 sq.ft.	Cost/ sq ft	Packed Vol,ft3	Usable Vol,ft3	Weight, lbs	Usable Area,ft2	Assembly MH	Cost ($1000)	Cost Year
TEMPER	51.2	0.391	0.94	11.88	100	5120	2000	640	8.00	*7.6*	c. 1989
H.E. GPM	102.4	0.139	0.39	2.15	40	4096	569	512	2.67	1.1	c. 1989
THE	900.0	0.056	0.54	5.56	40	*36000*	2000	1800	13.00	*10.0*	c. 1989
ISO 2:1	1.5	2.910	0.47	176.69	1280	1890	5500	266	1.67	*47.0*	c. 1989
ISO 3:1	2.2	2.464	0.58	156.41	1280	2800	6900	390	3.00	61.0	c. 1989
S-530	2.4	1.266	1.45	215.52	660	1580	2000	232	4.50	*50.0*	c. 1989
H.B. ESC	2.7	1.843	2.63	182.46	850	2290	4220	285	10.00	52.0	c. 1989
Army EXP	5.2	1.210	1.29	107.53	1280	6610	8000	930	16.00	*100.0*	c. 1989
MERWS + ISO 2:1	6.8	1.484	1.11	108.33	1280	8640	12820	1080	16.00	*117.0*	c. 1989
H.B. EXP	12.5	0.805	1.72	91.95	285	3570	2875	435	10.00	*40.0*	c. 1989
H.B. GP	30.9	0.667	4.50	68.67	485	15000	*10000*	1500	90.00	103.0	c. 1989
H.B. ACH	53.2	0.387	1.82	42.61	1940	103275	*40000*	9670	132.00	412.0	c. 1989
Foam Dome	55.3	0.482	5.42	12.05	*60*	3320	1600	415	30.00	*5.0*	*c. 1989*
K-Span	41.0	0.503	1.36	17.61	2910	119250	*60000*	7950	144.00	*140.0*	c. 1989

Notes:
1. 20% of equipment allocated to each foam or K-span shelter
2. Foam dome is 28 feet in diameter (CERL-TR-M-255)
3. K-Span is MIC-120 system (72 feet by 150 feet by 22 feet)
4. Italicized entries are either estimates or projections



a. Packing Ratio *vs*. Weight Ratio



b. Assembly Rate *vs*. Cost

Figure 13. Bare Base, Tactical, and Field Manufactured Shelter Attributes.

the upper left region of the figure and the tactical shelters are in the lower right region. Most of the current bare base shelters are clustered in the central portion of the figure. Also, as the size of shelters with given construction type (*e.g.*, frame-supported panel shelters) increases, the weight ratios tend to decrease and the packing ratios tend to increase. This trend indicates that the attributes are not fully normalized across shelters of all sizes.

The assembly rate and unit cost attributes are plotted in Figure 13.b. Here, the trend is generally up and to the right; however, there is considerably more scatter than in Figure 13.a. As in Figure 13.a, the three fabric shelters are among the best performers. The bare base shelters tend to follow the trend established by the fabric shelters. The outliers in Figure 13.b are the small tactical shelters (high cost, rapid assembly) and the foam dome (low cost, slow assembly).

b. Air Mobility Catalog Attributes

The shelter attributes for this group of shelters are summarized in Table 4. This data was collected in approximately 1975. Since the packed volumes were not listed in many cases, the data set is not complete. Most of the shelters are either fabric shelters or small box-type shelters. Many of the remaining shelters are predecessors to the bare base shelters listed in Table 3. There are also several conceptual shelters that apparently never came into use.

c. Tentage Reference Manual Attributes

The shelters listed in Table 5 are exclusively fabric shelters. The list includes pole-, frame-, and air-supported fabric shelters and shelter concepts. Except for packed volumes, the data listed for the standard shelters is fairly complete. The relatively up-to-date shelter cost data is particularly useful. Overall, Table 5 dramatically reinforces the mobility and cost advantages of fabric shelters. Except for a few isolated cases (*e.g.*, chemical-biological shelters), the weight, assembly, and cost attributes of these shelters range from very good to excellent.

d. Summary

Obviously, the attributes considered in this section do not present the entire picture. If these four attributes were the only driving factors in the shelter selection process, fabric shelters would be the clear-cut choice. This point reinforces the importance of the additional portable shelter objectives specified in the FOPS ORD such as durability, habitability, survivability, etc. An analysis that addresses all of these conflicting shelter objectives is presented in Section IV. The existing shelter data tabulated in this section forms the basis for our estimates of the mobility and unit cost attributes of the candidate shelter concepts evaluated in Section IV.

TABLE 4. AIR MOBILITY CATALOG SHELTER DATA.

Shelter	Packing Ratio	lbs/ cu ft	MH/75 sq.ft.	Cost/ sq ft	Packed Vol,ft3	Usable Vol,ft3	Weight, lbs	Usable Area,ft2	Assembly MH	Cost ($1000)	Cost Year
Elect. Equip.	1.0	2.810	1.23	0.00	427	427	1200	61	1.00		
Elect. Equip.	1.0	1.954	0.84	74.16	614	614	1200	89	1.00	6.6	c. 1975
Atco Portable		0.498	4.48	3.32		56200	28000	4020	240.00	13.3	1970
Elect. Equip.	1.5	2.865	0.14		1280	1920	5500	271	0.50		
Utility Shelter	38.1			14.58	432	16470		1372		20.0	1973
Porta-Kamp Diner	3.2	3.333	2.00	12.33	1494	4800	16000	600	16.00	7.4	c. 1975
Aircraft Maint.	67.1	0.140	2.62	9.79	1280	85840	12000	4292	150.00	42.0	c. 1975
GP Shelter	30.7	0.393	1.30		540	16560	6500	1300	24.00		
Prefab Panelized	16.7	0.892	5.08	8.65	460	7680	6850	960	65.00	8.3	1952
Northrup Knockdown	4.0	2.344			320	1280	3000	160			
Dual Wall Infl.			1.63	7.60		82944		4608	100.00	35.0	c. 1975
Single Wall Infl.		0.103				48434	5000	2705			
Air Supp. Tent		0.059	3.10	6.46		100000	5920	4647	192.00	30.0	1973
Air Supp. Radome		0.181	1.57	1.92		5400	978	572	12.00	1.1	1973
Accordian Tent		0.141	1.50	4.45		1600	225	200	4.00	0.9	1973
GP Tent		0.176	0.35	0.46		25600	4500	2855	13.50	1.3	1973
GP Tent		0.171	1.13	2.10		1500	257	200	3.00	0.4	1970
Pop-up Tent		0.070	0.28			616	43	88	0.33		
Artic Pers. Tent		0.615	2.92	5.06		650	400	77	3.00	0.4	1970
GP Tent		0.223	0.44	0.98		2560	570	512	3.00	0.5	1970
Pers. Tent		0.169	1.26	4.41		1780	300	356	6.00	1.6	1970
Maint./Storage Tent		0.446	3.75	4.53		8960	4000	640	32.00	2.9	1970
Frame-Type Tent		0.791	0.95	4.16		2848	2252	356	4.50	1.5	1973
Disp. Fcam Panel						4096		512			
Polycom (accordian)		0.099	0.94	2.81		3570	355	320	4.00	0.9	1973
Stressed Membrane	238.0	0.047	6.67		416	99000	4700	4500	400.00		
Ext. A/C Maint.		0.133	1.00	13.07		225000	29900	7500	100.00	98.0	1972
Birdair Mk66 Hangar	145.4	0.104	6.01		557	81000	8400	4990	400.00		
Frame Supp. Maint.		0.137	4.17	3.36		38000	5189	1728	96.00	5.8	1973

TABLE 5. TENTAGE REFERENCE MANUALSHELTER DATA.

Shelter	Packing Ratio	lbs/ cu ft	MH/75 sq.ft.	Cost/ sq ft	Packed Vol,ft3	Usable Vol,ft3	Weight, lbs	Usable Area,ft2	Assembly MH	Cost ($1000)	Cost Year
Standard:											
Shelter Half Tent		0.100	0.24	1.60		50	5	25	0.08	0.04	1989
2 Man Mtn. Tent		0.234	0.77	2.19		64	15	32	0.33	0.07	1989
Tent, Hexagonal		0.083	0.83	6.28		678	56	113	1.25	0.71	1989
Tent, Arctic		0.066	1.01	6.20		1150	76	200	2.70	1.24	1989
Tent, GP Small		0.116	0.75	5.15		1600	186	200	2.00	1.03	1989
Tent, GP Medium	102.4	0.139	0.39	2.15	40	4096	569	512	2.67	1.1	1989
Tent, GP Large		0.102	0.60	1.32		7488	761	936	7.50	1.24	1989
Tent, Command Post		0.199	0.73	5.12		1290	257	172	1.67	0.88	1989
Tent, Assembly		0.069	0.70	1.50		25600	1755	3200	30.00	4.80	1989
Tent, Frame-Type		0.167	0.88	7.19		1792	300	256	3.00	1.84	1989
Tent, Maint.		0.335	1.28	5.30		3744	1255	468	8.00	2.48	1989
Tent, Maint, Med.		0.512	2.34	20.78		6400	3276	640	20.00	13.30	1989
Chem-Bio Trailer			1.13	281.00		1600		200	3.00	56.20	1989
Air-Infl, Dbl. Wall		0.537	0.61			11840	6356	1480	12.00		
Developmental:											
Hansen Weatherport		1.100	1.32	53.40		2048	2252	256	4.50	13.67	1989
Vehicle CB Tent		0.214	0.47	0.00		280	60	80	0.50		
Collect. Prot. Tent		0.131	0.25	5.33		2100	275	300	1.00	1.60	1989
Extension Shelter	200.0	0.090	0.25		4	800	72	100	0.33		
Cold Weather Shelter							5		0.33	0.08	1989
CB Protected System		0.271				2400	650	300			
TCPS			1.20	12.00		1750		250	4.00	3.00	1989
Mod. L.W. Hex. Tent		0.149	0.05	10.62		565	84	113	0.08	1.20	1989
5 Soldier Crew Tent		0.200	0.06			400	80	100	0.08		
SICPS		0.284	0.42			968	275	121	0.67		1989

C. SHELTER COMPONENTS AND SUBSYSTEMS

Three basic elements of the shelter design concepts are considered in this section: overall geometry, structural system, and cladding or environmental barrier system. In addition to these three basic subsystems, weapon effects survivability subsystems represent a unique new component for the next FOPS. Our goal in this section is to classify basic subsystem design options according to their common characteristics. A similar, but separate, treatment is given to survivability enhancement systems in Section III. The purposes of this methodical review are to expand upon the design characteristics reviewed in Section B and to limit the chances of overlooking potential design innovations and to provide a sound basis for the concept synthesis task presented in Section D.

We recognize that in many cases the geometric, structural, environmental, and hardening systems can be deeply intertwined. In pole-supported tents, for example, the fabric serves as both the environmental barrier and as an integral component of the primary structural system, and the geometry is limited to configurations in which tension can be maintained in the fabric under all anticipated loading conditions. If we also select a fabric that provides ballistic protection, we see that all three basic subsystems and the survivability subsystem can potentially be represented in one shelter component. A shell structure (*e.g.*, a foam dome) is another example of a shelter with integrated subsystems. For shells, the geometry essentially defines the structural system, and the structural system is also the cladding. Although we organize design alternatives on a subsystem-by-subsystem basis in this section, this approach is not meant to preclude the likelihood that many of the candidate design concepts will be composed of multipurpose, integrated components. An all-in-one, integrated geometric, structural, environmental, and hardening system would obviously bring many efficiencies to a design concept. However, these efficiencies must be considered within the scope of the special requirements for airmobile shelters. Section IV presents our framework for comparing shelter concepts.

1. Shelter Geometries

There is an infinite variety of possible shelter geometries. In this section, we enumerate several classes of potential overall geometries for airmobile shelters. Our focus is on potential shapes for the basic shelter units. Since modularity and extendability are important design objectives for the new FOPS, these issues are considered with respect to the suitability of each basic geometry. A study on optimal shelter dimensions based on weight and survivability criteria is presented in Appendix F.

a. Planar Solids (Polyhedrons)

From the perspectives of manufacturability, cost, transportability, and interchangeability, shelter geometries having flat, planar surfaces offer many advantages. We will divide planar solids into two groups: (1) simple planar solids having four, five, or six surfaces, and (2) complex planar solids with more than six surfaces. Among planar solids, geometries with more than six surfaces will generally offer the best combination of interior space efficiency and structural efficiency for the small and large shelters considered in this study.

(1) Simple Planar Solids

The simplest planar surface solids are the tetrahedron and pyramid shown in Figures 14 and 15, respectively. These shapes have obvious drawbacks in terms of usable floor space and in the potential for extending or modularizing the shelter. The prism or "pup tent" geometry (Figure 16) is the simplest extendable solid. However, the problem of maximizing interior space efficiency is only partially alleviated with the prism. Thus, we conclude that the tetrahedron, pyramid, and prism are generally impractical geometries for the large majority of portable shelter applications.

The rectangular parallelepiped or simple box shape (Figure 17) is the simplest common shelter geometry. Current box-shaped shelters include most of the DOD standard family of tactical shelters and the AF bare base small span rigid wall shelters (*i.e.*, ESC, EXP[1]). The box shape is generally the geometry of choice for small span shelters with expansion ratios of 3:1 or less. Unless roof trusses are used, flat roofs are generally structurally inefficient for the 20-*foot* spans of the small shelters considered in this study. However, the existing box-shaped shelters do confirm that flat roofs are feasible for smaller spans in the range of 8 to 14 *feet*.

Most non-rectangular parallelepiped geometries are impractical for airmobile shelters. A possible exception is the extruded trapezoidal solid (Figure 18). Sloping two of the wall surfaces inward reduces the roof span and allows arching effects to be developed (provided continuity is maintained in the wall/roof connections). An interesting benefit of inclined wall geometries, such as the extruded trapezoid, is the potential for improved survivability against lateral fragmenting weapon effects by forcing oblique impacts. This concept is further explored in Section III.G. There are currently no portable shelters that have purely trapezoidal cross-sections. However, the TEMPER and the Harvest Bare GP shelters, with their shallow-pitched roof sections, are nearly trapezoidal. The need for pitched roofs in these two shelter designs are further evidence the inefficiency of flat roofs in lightweight portable shelters with spans of 20 *feet* or more.

(2) Complex Planar Solids

Among the infinite variety of polyhedral geometries, prismatoids are one important subset that may be suitable portable shelter geometries. Prismatoids are polyhedrons whose vertices lie in one of two parallel planes. By providing two parallel walls in the shelter geometry, we guarantee shelter extendability since the shelters can be arranged end-to-end to provide increased floor space. A smaller subset of polyhedral solids is prismoids. Prismoids are

[1]Although the EXP has the overall shape of a box, the expanding accordion foamboard sections are actually a complex arrangement of folded plates.

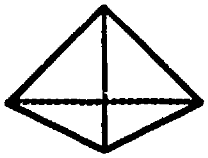


Figure 14. Tetrahedron.

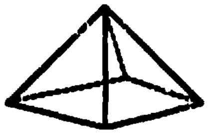


Figure 15. Pyramid.

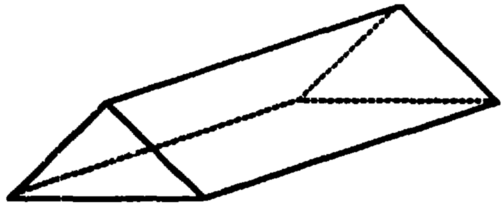


Figure 16. Prism.

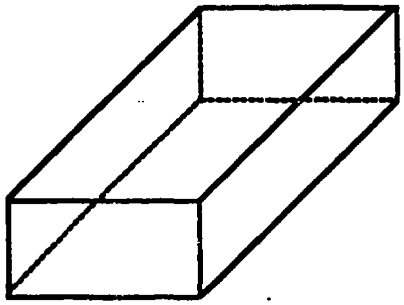


Figure 17. Rectangular Parallelepiped.

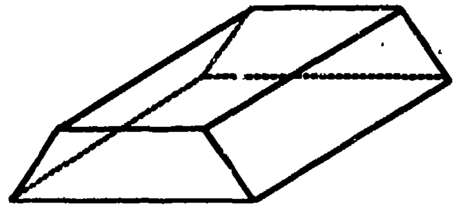


Figure 18. Extruded Trapezoid.

prismatoids having polygons with equals numbers of sides as its bases and quadrilaterals as its lateral faces. If we restrict the quadrilaterals to being rectangular to enhance packaging and transportability and if we align the rectangles perpendicular to the end sections, the result is the family of rectangular prismoids shown in Figure 19. This family of folded, flat-plate structures includes current shelters such as the TEMPER, the Harvest Bare GP, and the Harvest Bare ACH.[1]

b. Smooth Solids and Discrete Approximations

Due to the structural efficiency of smooth shells, there is considerable merit to smooth solid geometries for lightweight structures. Unfortunately, the requirements of portability and rapid assembly severely limit the materials and construction methods that can be used to erect portable shell structures. At this time, polymer foams appear to be the only feasible material for constructing a continuous, airmobile shell. However, the fact that foam shelters cannot be redeployed is a significant drawback. Although there are significant questions regarding the selection of a rigid shell geometry for the new FOPS, there are at least three other possible structural systems that are compatible with smooth geometries: (1) tensile membrane structures; (2) formed, repetitive shells such as the K-Span system; and (3) discretized, rigid panel approximations to smooth shells. Therefore, it is useful to consider the various types of smooth geometries that may be used in the new FOPS either directly or as a pattern for a discrete approximation.

[1] As the number of rectangular sufaces increases (*e.g.*, the ACH shelter), the rectangular prismoids become discrete approximations to a half-cylinder.

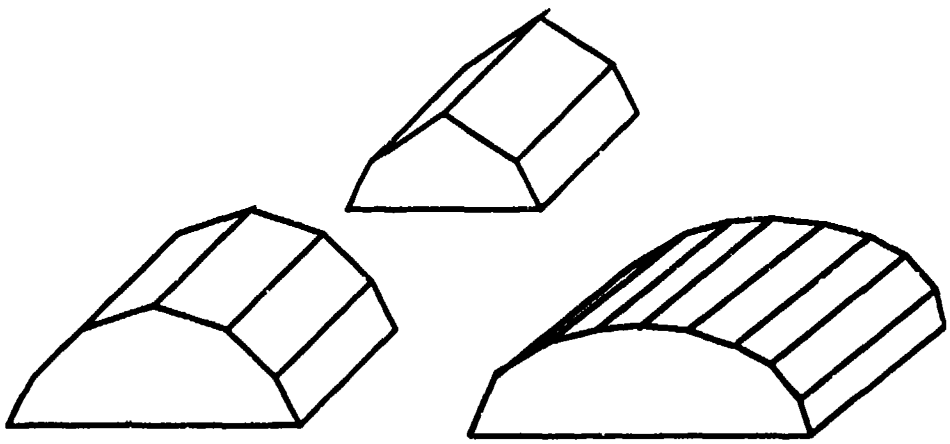


Figure 19. Rectangular Prismoids.

One method of classification for smooth three-dimensional surfaces is as either surfaces of revolution or as surfaces of translation. Surfaces of revolution include cones, circular paraboloids, circular ellipsoids, and circular hyperboloids. Surfaces of translation are generated by translating one plane curve over another plane curve (see Figure 20). Examples of surfaces of translation include cylinders, hyperbolic paraboloids, elliptic paraboloids. The latter two surfaces are formed by translating convex parabolas over concave or convex parabolas, respectively. Although surfaces of revolution and translation are helpful methods for visualizing the generation of a three-dimensional surface, these classifications have little general merit with regard to structural action [Billington, 1965].

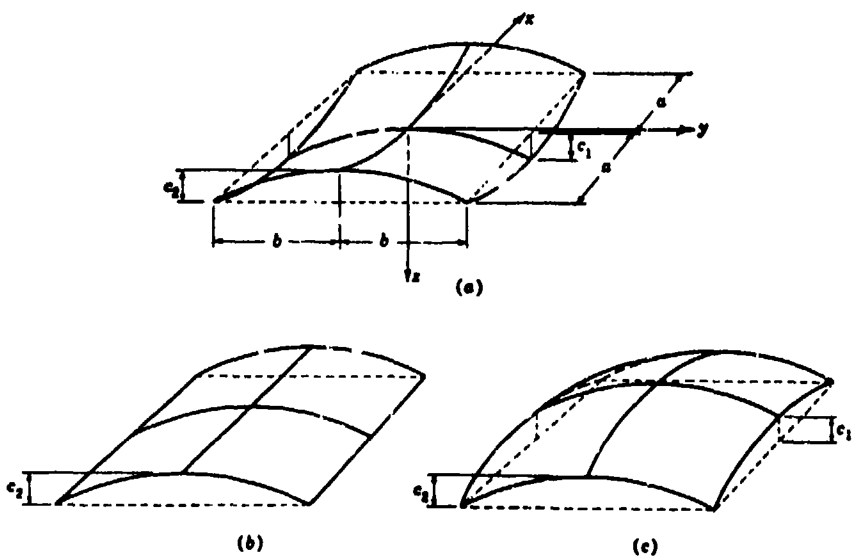


Figure 20. Surfaces of Translation [Billington, 1965].

A more useful method for classifying three-dimensional surfaces is according to the curvature of the surface [Billington, 1965]:

1. Synclastic surfaces or surfaces of positive gaussian curvature have both centers of curvature on the same side of the shell surface. Domes are synclastic surfaces of revolution that serve primarily as roof structures. Examples include spherical, conoidal, and elliptical domes (Figure 21). Elliptic paraboloids (Figure 20.c) are an example of synclastic surfaces of translation. Synclastic shells are generally well approximated by membrane theory except at the regions very near to the shell boundaries where bending forces are significant.

2. Surfaces of zero gaussian curvature or singly curved surfaces have zero curvature in one direction. Examples of singly curved surfaces are the cylinder and the cone. Edge effects are generally more prominent in singly curved shells than in synclastic shells.

3. Surfaces of negative gaussian curvature or anticlastic surfaces have one center of curvature on either side of the surface. Examples of anticlastic surfaces include hyperbolas of revolution and hyperbolic paraboloids (Figure 22). Anticlastic surfaces are particularly important for lightweight portable shelters since these are the only geometries in which a tensile membrane can be suspended. Thus, any concepts employing edge-supported fabric roofs must have anticlastic roof geometries.

There are many boundary geometries for three-dimensional surfaces that may be applicable to portable shelter design. Cylindrical arch shelters, for example, can be semi-cylindrical (half angle of 90 *degrees*) or have half angles of less than 90 *degrees*. For large span shelters (such as the current Harvest Bare ACH), half angles in the neighborhood of 70 *degrees* are commonly selected as a good compromise between structural requirements and interior space requirements. Spherical domes can also be cut along a latitude to produce a half angle of less than 90 *degrees* or they can be cut along other curved lines in their surface as shown in Figure 21. Hyperbolic paraboloids can be cut into saddle shapes with parabolic edges, or they can be cut into curved panel sections with straight edges (Figure 22).

Smooth three-dimensional surfaces can also be used to form the walls of a shelter. Possible examples include vertically oriented cylinders or hyperbolas of revolution. However, these geometries are typically chosen for pressure vessels and/or tall, slender structures (such as cooling towers) and are not generally appropriate for the typical bare base shelter functions considered in this study. Another example is the circular torus, which is formed by rotating a circle about an axis in the plane of the circle that does not cut the circle. Such a geometry has been recommended for a pressurized lunar shelter [Chow, 1992]. Each of these geometries is inherently non-extendable and difficult to modularize.

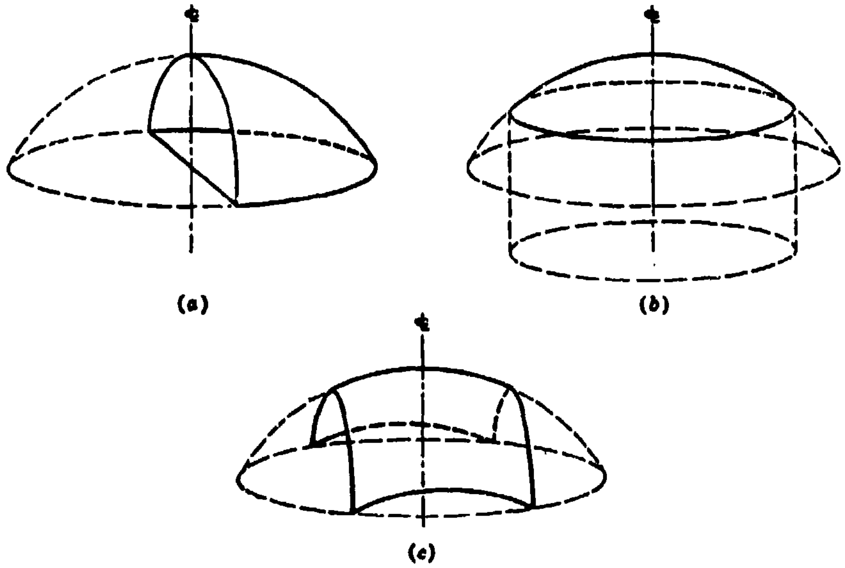


Figure 21. Spherical Domes [Billington, 1965].

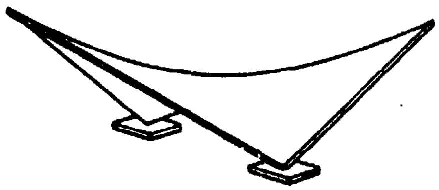


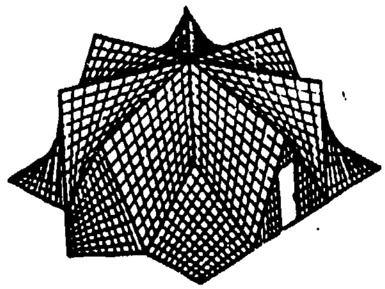
Figure 22. Hyperbolic Paraboloid [Winter and Nilson, 1979].

c. Other Geometries

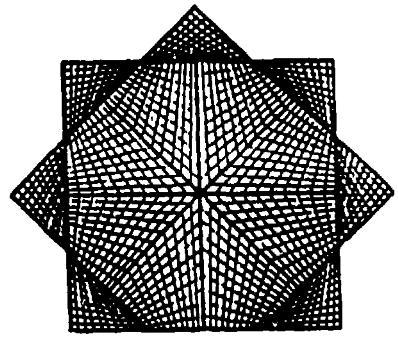
Aside from the convex polyhedral solids discussed in Section II.C and discrete approximations to smooth curved surfaces (such as a geodesic dome), there are additional families of folded surfaces that may be suitable for portable shelters. One current example is the complex geometry of the Harvest Bare EXP accordion shelter. The expandable walls and roof of the EXP are composed of a series of non-convex folded plates that can be tightly packed into the shelter container for transport. An example of a curved folded surface shelter is the HUTCH hyperbolic paraboloid shelter [Moriarty and von Buelow, 1989] (Figure 23). The basic unit in the HUTCH family of shelters is made up of 16 hyperbolic paraboloid panels joined along their straight edges to approximate a dome shelter.

d. Summary

Potential geometries suitable for portable shelter design are summarized in Table 6. These geometries can be incorporated into the entire shelter, the roof, or the walls.



a. Isometric



b. Plan

Figure 23. HUTCH Hyperbolic Paraboloid Shelter [Moriarty and von Buelow, 1989].

TABLE 6. SUMMARY OF CANDIDATE GEOMETRIES.

Planar Solids		Smooth Solids			
Simple	Complex	Synclastic	Singly Curved	Anticlastic	Other
• Tetrahedron • Pyramid • Prism • Rect. Parallelepiped • Extruded Trapezoid	• Prismoids - TEMPER - GP - ACH - etc.	• Domes - Spherical - Elliptical - Conoidal - Parabolic	• Cylinder • Cone	• Hyperbola of Revolution • Hyperbolic Paraboloid	• Toroid

In many cases, the smooth three-dimensional geometries will serve as templates for discrete panel approximations. For example, a geodesic dome is a discrete approximation to a smooth, spherical dome. The shelter concepts synthesized in Section D all have geometries that are based on the solid surfaces presented in this section.

2. Structural Systems

a. Discrete Structural Elements and Systems

In this section, we review discrete (essentially one-dimensional) structural elements and the structural systems that can be generated from these elements. Trusses and rigid frames are the two most basic types of structural systems formed from discrete structural members [McCormac, 1975]. While trusses offer the potential for rapid assembly in the form of pantographs [Hernandez, *et al.*, 1991], frames are generally more ductile and better able to survive the severe impulsive loads that can be produced by conventional weapons.

(1) Axial Elements and Systems

Ties and struts are the two most basic structural elements. Ties are straight axial members that resist longitudinal tensile loads, while struts are straight axial members that resist in-line compressive loads. Since struts are loaded in compression, some bending strength must be provided to prevent instabilities that would inevitably result due to load eccentricities or material imperfections. Cable ties and slender tie bars must only be used if the member will remain in tension under all anticipated load combinations.

Trusses are formed by triangular combinations of pin-connected axial members. Flat, one-way trusses essentially act as deep lightweight beams. Curved, one-way trusses can be employed in arched, cylindrical geometries. Two-way trusses and space trusses can be used to approximate plate or shell behavior. An interesting application of truss systems is the pantograph (Figure 24). A pantograph is an unstable truss that can be locked into a highly expanded configuration. This feature makes pantographic construction very attractive for structures that must be transported and rapidly assembled [Hernandez, *et al.*, 1991] Under many instances, trusses can be designed such that many elements are only exposed to tensile loads. One example of a truss system that makes extensive use of cable ties is the tensegrity structure [Levy, 1991].

A less frequent application of structural ties is in reinforced earth walls. In these systems, grids of tensile members are used to provide lateral support to interlocking retaining wall panels. Although reinforced earth is not typically rapidly erectable or portable, such systems may be necessary for a few selected shelter functions that merit significant survivability measures.

A final class of axial members and structures is cables. Cables differ from ties in that they are curved axial members that are designed to resist transversely applied loads rather than longitudinally applied loads. Cables are often combined with struts to form a structural system. A simple example is the cable "beam" system shown in Figure 25. More complex, anticlastic curved surfaces can be generated by cable nets as shown in Figure 26.

(2) Axial/Flexural Elements and Systems

The fundamental flexural and axial/flexural structural elements are beams, beam-columns, and arches. Beams resist transverse loads primarily through flexural resistance. Beam-columns and arches support transverse and longitudinal or radial forces through a combination of flexure and axial resistance. A somewhat unconventional type of discrete flexural element is the air beam. An air beam is a pressurized bladder that resists transverse loads through moment couples that are set-up by a reduction in the tensile stress on one side of the bladder and an increase in tensile stress on the opposite side. The maximum moment capacity is therefore governed by the level of prestressing in the bladder membrane which, in turn is governed by the air pressure inside the bladder.

Rigid frames are structural systems composed of beams and beam-columns. Some or all of the connections in a rigid frame are moment resisting. The rigid joints provide the mechanism for resisting lateral loads. The rectangular prismoid and cylindrical geometries discussed in Section II.C.1 can be supported by a series of plane, two-dimensional

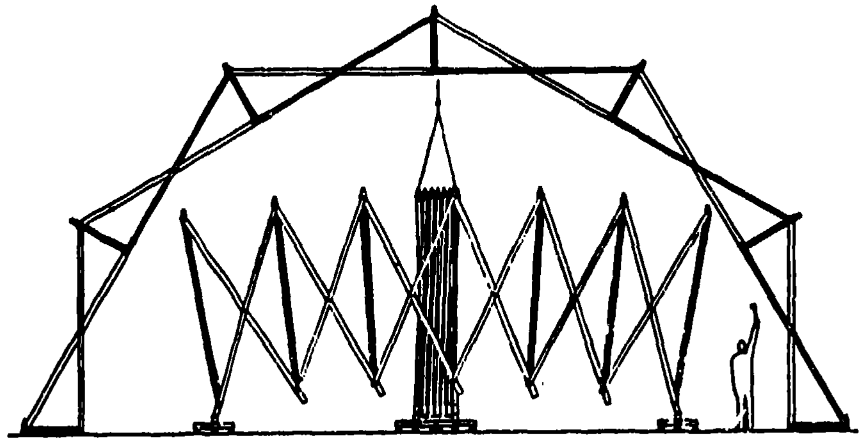


Figure 24. Deployable Pantographic Truss [Hernandez, *et al.*, 1991].

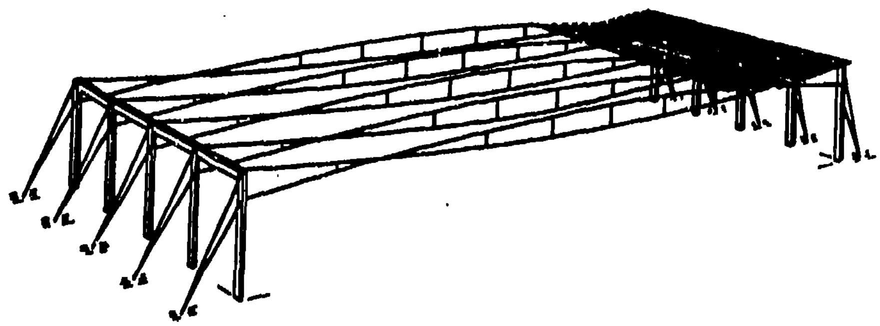


Figure25. Cable Beam Roof [Buchholdt, 1985].

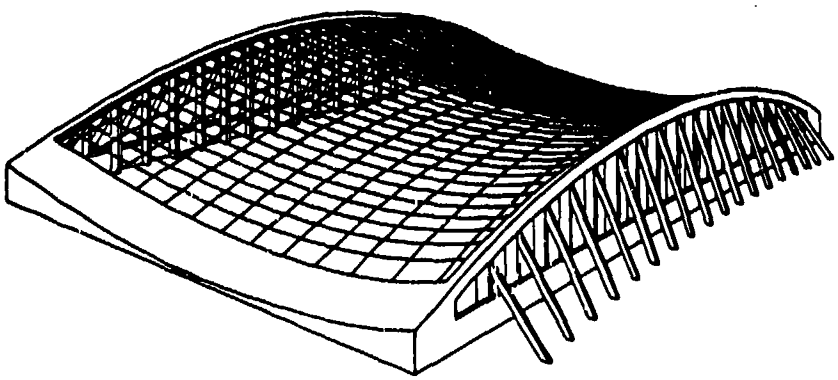


Figure 26. Cable Net Roof [Buchholdt, 1985].

frames or arches that are equally spaced between the parallel end-surfaces. Three-dimensional frames are often incorporated into the edges of small, box-type shelters. Intersecting arches or frames can provide structural support for smooth surfaces of revolution or their discrete approximations.

b. Continuous Structural Elements and Systems

Continuous structural elements and systems can be classified according to their geometry (flat surfaces *vs.* curved surfaces) or according to their primary load carrying mechanism (axial *vs.* axial/flexural). Consistent with our discussion of discrete structural elements, we will focus on the structural distinctions.

(1) Axial Elements and Systems

Load-bearing walls are built-up, flat panels that primarily resist gravity loads and in-plane shear forces. However, provisions must be made to resist secondary lateral loads. Block walls are typically reinforced to provide necessary bending strength. Another alternative is to brace the wall with a perpendicular wall or with guy wires.

Membranes are the curved surface analogs to cables. They resist transverse loads through normal tensile forces only. As discussed in Section II.C.1.b, curved structural surfaces can be classified according to their type of curvature (positive, zero, or negative gaussian curvature). Unless they are sufficiently prestressed to prevent compressive internal forces under all anticipated loading conditions, membranes must be negatively curved to maintain their shape under transverse loading. In the context of portable shelters, prestressing via internal overpressure is a common strategy for achieving positively curved membrane geometries.

(2) Axial/Flexural Elements and Systems

Plates are flat structural elements that primarily resist transverse loads. The thicknesses of plates are small compared to their length and width dimensions. Since plates are primarily flexural members, it is often most efficient to concentrate the materials at each surface with a lightweight core material providing transverse shear strength. The resulting structural element is typically referred to as a sandwich panel. The sandwich panel is a two-dimensional analog to the standard structural I-beam. Aluminum skin sandwich panels with honeycomb or foam cores are the norm for virtually all existing portable shelter panels. Potential variations include stiffened sandwich panels or stiffened plates. Significant increases in sandwich panel performance may be possible with new materials for the skins, cores, and/or stiffeners.

Shells are curved surface elements whose thicknesses are small compared to their other dimensions. Although shells are highly efficient structural elements, there are major drawbacks that limit their applicability to portable shelter design. Smooth continuous shells must be formed and constructed in-place, a time consuming construction method that requires suitable materials. Currently, lightweight foams appear to be the only suitable materials for constructing portable, smooth shell structures; however, foam shells are subject to creep and are not redeployable. Possible alternatives are to assemble as shell from either prefabricated components or components that are formed in the field. In the former case, many connections would be required, which would make it difficult to approximate true shell behavior, and it would also be difficult to efficiently package and transport the curved, irregular shell components. An example of the latter case is the K-Span corrugated cylindrical shelter described in Section B.4.b.

c. Hybrid Structural Systems

Finally, we consider structural systems that employ both discrete elements and continuous elements. Perhaps the most common lightweight hybrid structural system is the pole-supported tent. These shelters are comprised of discrete struts and ties and a continuous fabric membrane. Another class potential hybrid systems is frame-supported roof membranes or shells. In these systems, frames transfer the edge reactions of the roof membrane or shell to the foundation and provide support to the wall cladding. For the shelter geometries and materials considered in this study, however, this type of structural system would generally tend to be bulky and unnecessarily complex. Finally, hybrid structural systems employing a combination of frames and shear wall panels are frequently used in portable shelters. For example, the cladding panels in the Harvest Bare GP and ACH shelters provide stability against loads perpendicular to the arched frames. Frame/panel hybrid construction can also be seen in of many current box-shaped shelters (*e.g.*, tactical shelters, the ESC, and the EXP).

3. Cladding Systems

Cladding system functions include providing environmental protection, providing weapon survivability, and serving as an integral component of the main structural system. Among these functional characteristics, environmental protection is the most fundamental since this is the primary purpose of any shelter. Cladding systems must protect the shelter occupants and contents from temperature variations, precipitation, wind, etc. A desirable secondary function for a military shelter cladding system is to enhance occupant survivability against weapon threats. Improved survivability can be provided in the form of CCD (camouflage, concealment, and deception), chemical-biological protection, airblast protection, small arms protection, and fragment protection. The latter three types of protection are treated in Section III.

The issue of shelter cladding is primarily an issue of materials selection. Material properties determine which functions a given cladding system can perform (*i.e.*, environmental, hardening, and/or structural) and whether a multi-layer cladding will be necessary. The review of shelter fabrics and panel materials in the following subsections and the analysis of hardening upgrades in Section III concentrate on materials suitable for providing ballistic and fragmentation protection. These results will serve as the basis for the selection of cladding systems and upgrades.

a. Fabrics

Table 7 summarizes the mechanical properties of commercially available fibers currently used in manufacturing fabric shelters and composite panels. The dominant fabric in current tentage and soft-walled shelters is vinyl-coated or vinyl-laminated polyester fabric. This dominance is due to polyester's availability, relatively high strength, durability, chemical resistance, and low-cost. This dominance, however, is being challenged by newer, high modulus aramid (Kevlar® or Nomex®) and polyethylene (Spectra®) fibers in many special applications where extremely high strength and/or ballistic protection is required.

Aramid fiber is the generic name for a class of synthetic organic fibers called aromatic polyamide fibers. Aramid fibers are ring compounds based on the structure of benzene as opposed to linear compounds used to make nylon, a long-chain polyamide. The fibers are spun from liquid crystal solutions of aromatic polyamides containing highly ordered arrays of extended polymer chains, producing fibers of an extremely oriented, chain-extended form that possess high molecular weight, high strength, and low density. Disadvantages of aramid fibers include low compressive strength (approximately one-tenth of its tensile strength) and degradation under ultraviolet (UV) exposure.

Kevlar® is the best known aramid fiber, having been produced commercially by Du Pont since 1971. Du Pont currently produces several types of Kevlar® fibers tailored to specific applications: (1) Kevlar® — meant mainly as a reinforcement for mechanical rubber goods such as tires, (2) Kevlar® 29 — meant for ballistic applications and coated fabrics for inflatable and architectural applications, and (3) Kevlar® 49 — meant for composite panel construction in aerospace, automotive, and sports applications. Du Pont recently introduced two new formulations of Kevlar®, providing improved properties for use in special applications. Kevlar® 129 provides increased strength (490,000 *psi)* and energy dissipation properties, enabling weaving of more efficient ballistic fabrics that are 15 to 20 *percent* lighter and 20 to 25 *percent* thinner than equivalent K-29 fabrics. Kevlar® KM2 is designed for improved ballistic performance in lightweight composite armors, offering 13 *percent* higher tenacity and 20 *percent* higher toughness while retaining the other physical and chemical properties of K-29. These property improvements provide an 8 to 10 *percent* increase in the 17-*grain* FSP ballistic resistance over K-29 composite laminates. This enables KM2 to provide equivalent performance to standard K-29 helmet shells at a 15 to 20 *percent* lower weight.

Spectra® is an ultra-high molecular weight polyethylene (UHMW-PE) produced by Allied-Signal, Inc. The fibers are produced by a special "gel spinning" process where the polymer is dissolved to disentangle the polymer chains. Fibers derived from the subsequent spinning possess low specific weight (0.97), high specific strength and modulus, high energy to break, high abrasion resistance, low moisture sensitivity, extremely high chemical resistance, good UV resistance, and good electrical properties. Spectra® has the lowest specific weight of the fibers listed in Table 7, and its high specific strength and modulus provide superior performance in many applications where high strength and low weight are important. Difficulties with Spectra®

TABLE II-6. MECHANICAL PROPERTY DATA FOR FIBERS.

Fiber	Specific Gravity	Elastic Modulus (*msi*)	Tensile Strength (*ksi*)	Elongation (*percent*)
Polyester	1.38	1.8	150	12-16
Nylon	1.18	0.56	102	20
Aramid				
- K29	1.44	10.6	425	3.6
- K49	1.44	18.0	525	2.9
- K129	1.44	13.9	490	3.3
- KM2	1.44	9.2	476	4.0
Spectra®				
- 900	0.97	17.4	375	3.5
- 1000	0.97	24.8	435	2.7
Fiberglass				
- E	2.55	6.5	160	4.3
- E HF	1.80	4.2	65	-
- S2	2.49	8.5	290	3.5
- S2 HF	1.80	6.9	210	3.0

include low adhesion properties, low melting temperature, and a tendency to creep at room temperatures. Spectra® is available in two fiber types: Spectra® 900 with a tensile strength of 375 *ksi* and modulus of 17.4 *Msi*, and Spectra® 1000 with an even higher tensile strength of 435 *ksi* and modulus of 24.8 *Msi*. Spectra Shield™ is a non-woven cross-ply laminate consisting of Spectra® fibers in a thermoplastic resin and is used as a lightweight, flexible ballistic armor.

The ballistic performance of fabric armors depends on wave propagation speed (specific gravity and elastic modulus) and tenacity of the materials. Kevlar® and Spectra® both have excellent properties in this respect. Other parameters, such as fiber denier also influence ballistic performance.[1] Figure 27 compares the relative ballistic performance of Kevlar® and Spectra® fabrics against 17-*grain* chisel-nosed fragment simulating projectiles (FSPs). Shown are the material areal densities required to stop the 17-*grain* FSP at a striking velocity of 1600 *feet/second* [Allied-Signal, 1992]. Two trends are noted. First, required areal densities for the Spectra® fabrics are generally lower than those for Kevlar®. Second, required areal densities decrease with decreasing fiber denier for both materials. This trend suggests that smaller denier K-29 fibers could outperform both Spectra® and the newer K-129 fibers. Figure 28 presents V_{50} data for 2, 4, 16, and 64-*grain* right circular cylinder FSPs.[2] For an equivalent weight fabric (1.26 *psf*), a 650-*denier* Spectra® fabric provides slightly better performance than a 1500-*denier* Kevlar® fabric. Spectra Shield™ provides comparable performance to the Kevlar® fabric, but with a 20 *percent* reduction in weight (1.01 *psf*); however, since data are not available for constant denier fabrics, it is not possible to separate material property and fiber denier effects.

---

[1]Fiber denier is a measure of fineness. One *denier* is defined as 0.05 *grams*/450 *meters*.

[2]The ballistic limit or V_{50} is defined as the velocity level at which a specific projectile has a 50 *percent* probability of completely penetrating the target material.

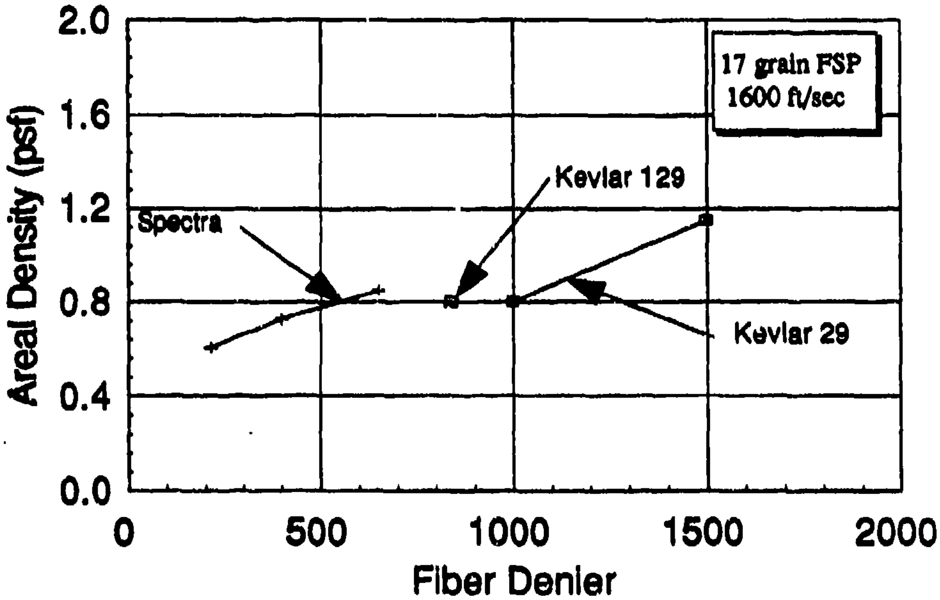


Figure 27. Variation of Areal Density Requirement with Fabric Material and Fabric Material and Fiber Denier.

b. Lightweight Composite Panels

Composite panels used to provide ballistic protection from small arms and fragmenting munitions are typically composed of S2-glass, Kevlar®, or Spectra®. The relative ballistic performance of these materials is illustrated in Figure 29.a which plots normalized V_{50}s for a select group of Kevlar® 29 and 49, Spectra® 900, and S2-glass panels tested by Bless, *et. al.* [1989] at the University of Dayton Research Institute (UDRI). The panels, which were being screened for potential use as lightweight armor on Air Force tactical shelters, had a nominal aerial density of 1 and 2 *pounds/foot*^{2} and varied fiber type, resin, and fabric density as summarized in Table 8. Spin stabilized 0.30 *caliber* FSPs (44-*grain*) were used to screen the candidate armors. The results showed that Spectra® 900 provided the protection level for this fragmentation threat at 1 *pound/foot*^{2} while the other candidate materials did not satisfy the goal of 2 *pounds/foot*^{2}. Kevlar® required slightly more than 2 *pounds/foot*^{2} while S2-glass required approximately 2.5 *pounds/foot*^{2}.

An interesting result from these tests was the relatively good performance of Kevlar® 49. The steeper slope of the V_{50} *vs.* armor demand curve for Kevlar® 49 suggests that

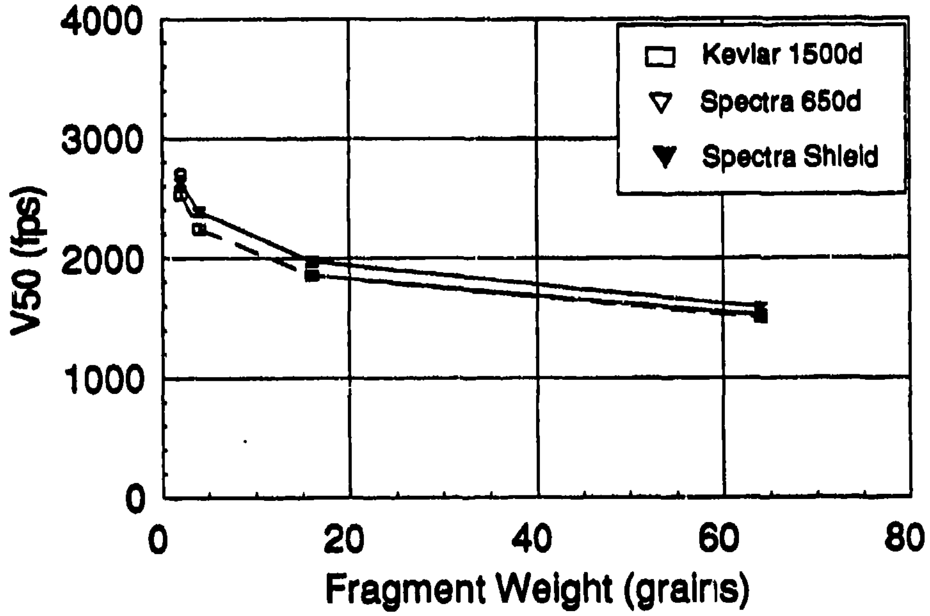
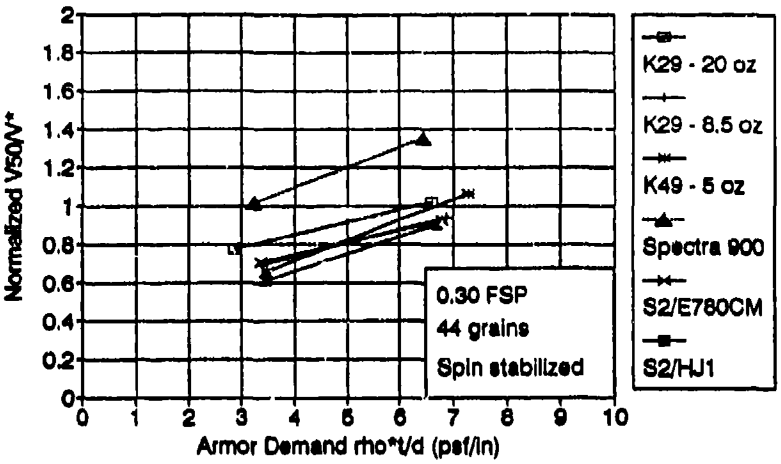


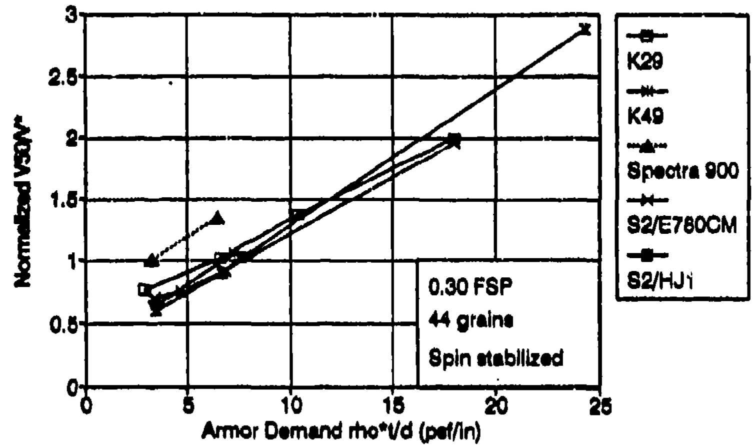
Figure 28. Ballistic Performance of Selected Kevlar® and Spectra® Fibers.

this fiber may outperform Kevlar® 29 at higher aerial densities. A similar observation is indicated for S2-glass in Figure 29.b which supplements the Bless, *et al.*, data with data provided by Owens Corning Fiberglass on S2-glass (HJ1 and E780CM resins) and Kevlar® 29 (PVB resin) at higher areal densities. These data show that S2-glass outperform Kevlar® 29 at higher areal densities. In addition to the potential weight and cost savings offered by S2-glass at these higher areal densities, S2-glass panels, because of its higher specific weight, will be approximately 30 *percent* thinner than a Kevlar® panel with the same areal density. Since integral fragment protection will most likely require areal densities in excess of 2 *pounds/foot*^{2}, the use of S2-glass, which is lower in cost than Spectra® and Kevlar®, may provide an attractive alternative.

The importance of the resin on the ballistic performance of composite panels was also demonstrated in the tests performed by Bless, *et. al.* [1989]. Kevlar® panels with proprietary resins provided by Hexcel and 3M (AF-32 nitrile phenolic) were tested using sabot launched 60-*grain* FSPs. These resins significantly enhanced ballistic performance of the Kevlar® fibers, as illustrated in Figure 30, which compares test results for these panels with test results for the Kevlar® and Spectra® panels discussed previously.



a. UDRI Data



b. UDRI and Owens-Corning Data

Figure 29. Relative Ballistic Performance of Solid Kevlar®, Spectra®, and S2-Glass Monolithic Panels.

With respect to environmental effects, Bless, *et. al.*, [1989] investigated degradation in the ballistic protection provided by lightweight rigid panels. The panels were nominally 2 *pounds/foot*^{2} in areal density and were constructed of Kevlar®, Spectra® 900, and S2-glass reinforced composites as discussed earlier in Table 8. Ballistic performance was evaluated at environmental extremes of: (1) dry at -40 *degrees* and +160 *degrees* Fahrenheit (F), (2) wet at room temperature, and (3) at +160 *degrees* F after exposure 120 *degrees* F and 95 to 100 *percent* relative humidity in an environmental chamber for a period of seven *weeks*. Upon removal from the environmental chamber, the panels were weighed to determine moisture gain and tested to determine V_{50}. Figures II-30 through II-32 summarize the V_{50} test results normalized to V_{50} at dry room temperature (DRT). Also plotted in these figures are the uncertainty intervals in the V_{50} data, based on the lowest velocity for complete perforation and highest velocity for partial perforation.

TABLE 8. MONOLITHIC COMPOSITE PANEL MATERIALS TESTED BY UDRI [adapted from Bless, *et al.*, 1989].

Panel Material	Type of Reinforcement	Number of Plies	Thickness (*inches*)	Areal Density (*psf*)	Resin	Weave
A	20 *ounces/yard²* Kevlar® 29	11	0.269	1.98	DOW Derakane 5104-40 vinylester resin	4 × 4 basket
B	8.5 *ounces/yard²* Kevlar® 29	24	0.288	2.06	DOW Derakane 5104-40 vinylester resin	1000 denier plain weave
C	5 *ounces/yard²* Kevlar® 49	40	0.290	2.18	Vinylester 8084 resin	Style 181
E	7 *ounces/yard²* Spectra®	32	0.375	1.92	E780CM polyester resin	21 × 21 plain weave
F	14 *ounces/yard²* S2-Glass	8	0.194	2.04	E70CM polyester resin	woven roving plain weave
G	24 *ounces/yard²* S2-Glass	8	0.198	2.09	E780CM FR polyester resin	woven roving plain weave
H	24 *ounces/yard²* S2-Glass	8	0.190	2.02	HJ1 phenolic resin	woven roving plain weave

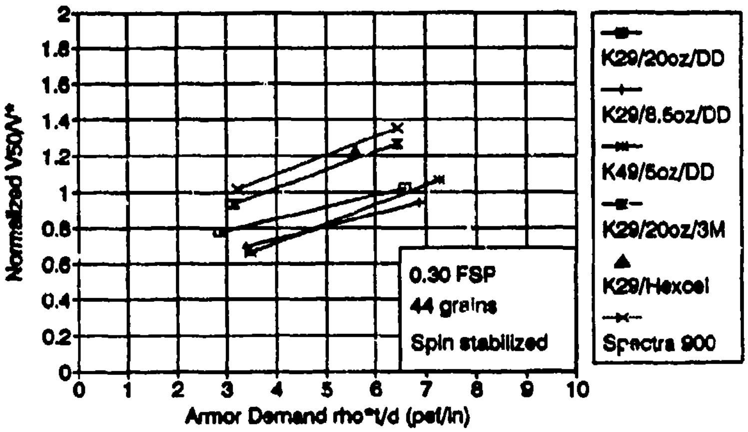
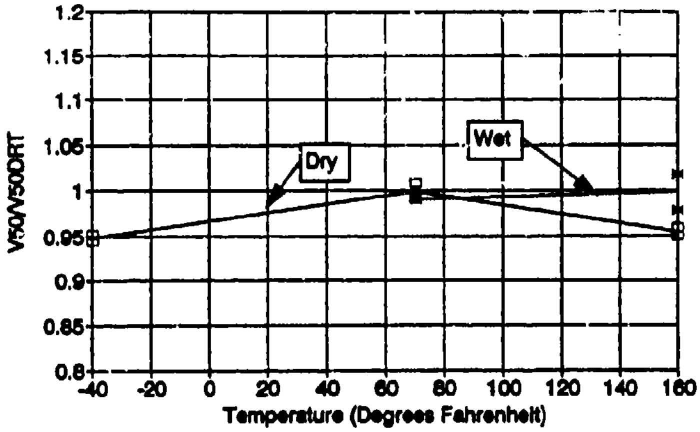
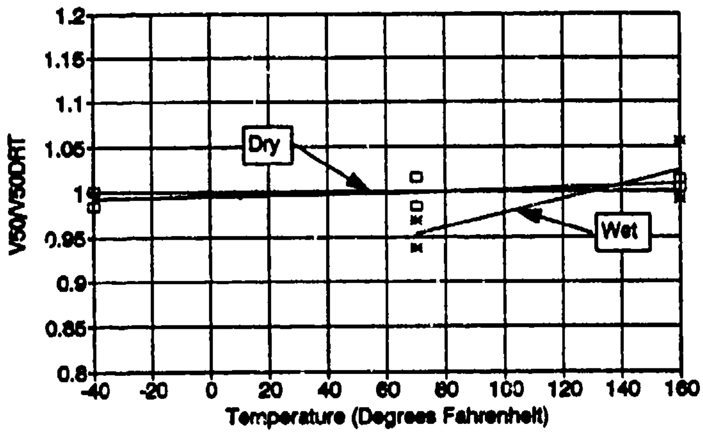


Figure 30. Ballistic Enhancement of Kevlar® with Hexcel® and 3M Resins.

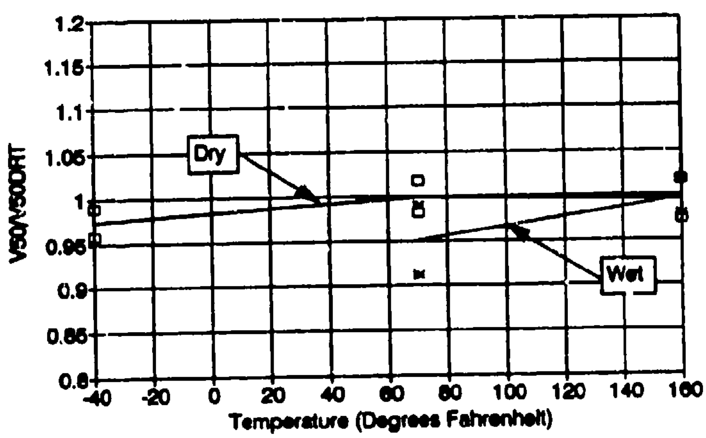
For the Kevlar® panels, only the 20 *ounce/yard²* data indicate a deviation from DRT properties due to the extreme temperatures. Ballistic limit velocities at -40 *degrees* F and +160 *degrees* F are 5 *percent* lower than those at DRT. While the small intervals between perforation and no perforation in the test data indicate this behavior may be representative of Kevlar® composites, this conclusion cannot be stated with confidence given the limited number of test shots. Data ranges are similarly small for the 8.5 *ounce/yard²* material which do not display this trend. Additionally, the single panel test data do not account for panel-to-panel variations in ballistic properties. Considering the conflicting trends in the 20 and 8.5 *ounces/yard²* data and the relatively small deviation from DRT properties, we conclude that the deviations most likely represent panel-to-panel variations. Conflicting trends are also noted in the wet test data at RT and



a. 20-*ounce* Fabric



b. 8.5-*ounce* Fabric



c. 5-*ounce* Fabric

Figure 31. Ballistic Performance Degradation of Kevlar® 29 Due to Moisture and Temperature.

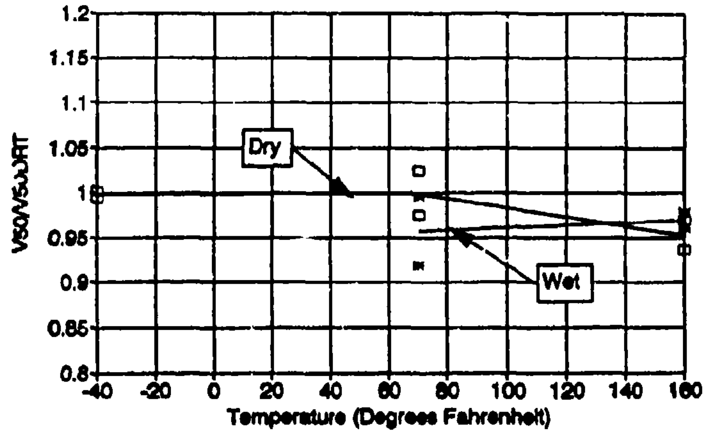


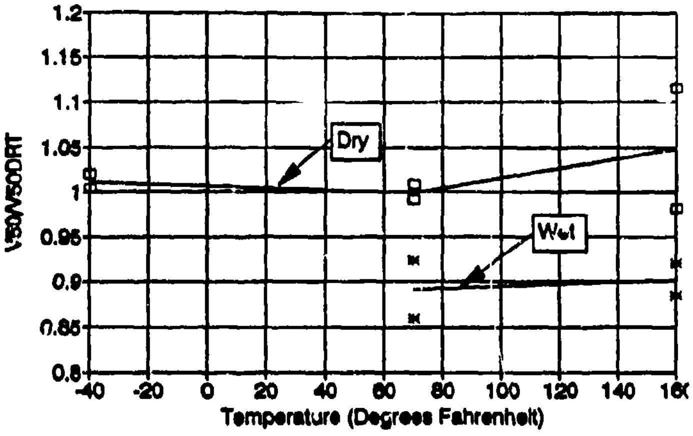
Figure 32. Ballistic Performance Degradation of Spectra® Due to Moisture and Temperature.

160 *degrees* F, with significantly larger data bounds. Again, we conclude that these deviations most likely reflect panel-to-panel variations and that the data is inconclusive with respect to ballistic protection degradation due to moisture.

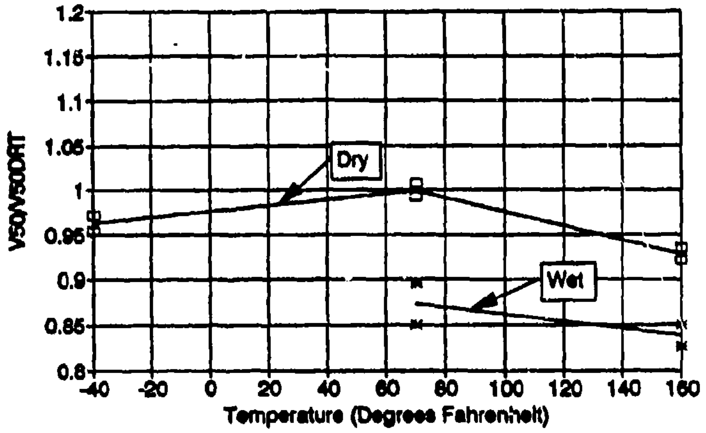
The Spectra® 900 data likewise is inconclusive due to the limited data and large intervals between perforation and no perforation. Polyethylene has a relatively low melting temperature so that property degradation is expected for Spectra® at high temperatures. This is consistent with the trend observed in the test data. Assuming the V_{50} for wet room temperature falls in the high end of the V_{50} date interval, we conclude that the moisture effect is minimal and that the degradation due to temperature effects is less than 5 *percent* at +160 *degrees* F.

The S2-glass/polyester panels demonstrated the greatest susceptibility to moisture degradation. Wet V_{50}s for these panels were 10 to 15 *percent* lower than DRT. Additionally, the flame retardant polyester resin displayed a temperature dependency with a five *percent* reduction at the two temperature extremes. The HJ1 phenolic resin fared much better, showing only a 3 to 5 *percent* in V_{50} due to moisture and little or no susceptibility to temperature extremes. In general, the test results indicate minimal moisture and temperature degradation for all the materials except the S2/polyester panels.

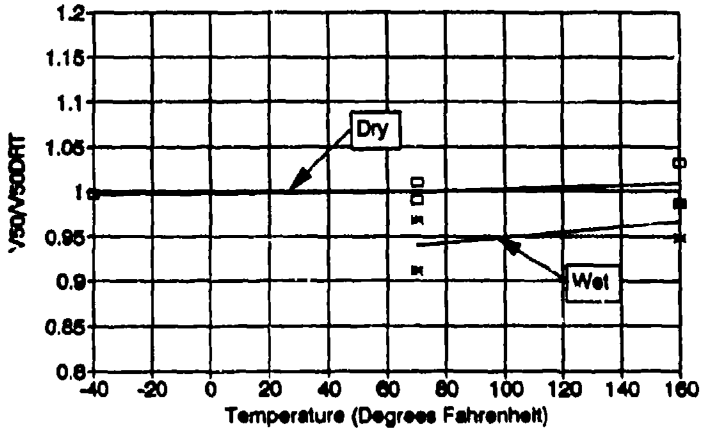
Another consideration with respect to ballistic panel selection is fire resistance. The secondary ballistic hazards of fire and smoke in enclosed areas such as shelters are of increasing concern to military planners. Table 9 compares flame and smoke indices for typical S2-glass and Kevlar® composites with typical NAVSEA (Naval Sea Command) guidelines for shipboard components [Owens-Corning Fiberglass, ND]. S2-glass, itself, is noncombustible and phenolic resins are fire-resistant and have low smoke emission levels. Fire-retardant formulations



a. E780-CM Polyester Resin



b. E780-CMFR Polyester Resin



c. HJ1 Phenolic Resin

Figure 33. Ballistic Performance Degradation of S2-Glass Due to Moisture and Temperature.

TABLE 9. FIRE AND SMOKE INDICES FOR S2-GLASS AND KEVLAR® [Owens-Corning, NDb].

	Limiting Oxygen Index[c]		Smoke Obscuration[d]		
	23C	150C	Flaming	Smoldering	Flame Spread Index[e]
NAVSEA Guidelines	>27	>27	<250	<250	<250
S-2 Glass Fiber/Phenolic	56	75	30	2	1[a]
Aramid/Vinylester[b]	39	39	405	152	13

[a] Data from FMI Corporation literature on typical glass/phenolic systems.
[b] Data from NSWC Report 80-302.
[c] *Limiting Oxygen Index* is a measure of the percent of oxygen required to sustain a flame in an oxygen/nitrogen stream of air. The higher the percent oxygen, the less flammable the material is.
[d] *Smoke Obscuration Index* is expressed in terms of specific optical density. The lower the number, the lower the amount of smoke, and thus the greater the visibility.
[e] *Flame Spread Index* is an indication of the rate a fire may spread. Once again, lower numbers equate to greater fire protection.

are also available for polyester resins (E780-CMFR); however, as mentioned earlier, the flame-retardant formulations did not perform well in environmental testing [Bless, *et al.* 1989].

D. SMALL AND LARGE SHELTER CONCEPTS

The synthesized shelter design concepts are presented in this section. Sixteen small shelter concepts and eight large shelter concepts are illustrated and defined in terms of the design attributes necessary for the concept evaluation and selection task (Section IV). At this point, only the basic shelter concepts are described. Several survivability upgrade systems are developed as a result of the hardening trade studies presented in Section III. These upgrades are considered in Section IV as design variations on the basic concepts presented in this section.

1. Small Span Shelters

The sixteen candidate small shelter concepts selected for consideration in the concept evaluation and selection task are presented in this section. Table 10 summarizes the shelter type and approximate dimensions for each concept. The shelters are classified according to the categories outlined in Section B. Sketches of the small shelter design concepts are shown in Figure 34. General observations on the benefits and drawbacks of each concept are reviewed in Section B.

Table 11 summarizes our best estimates for each of the 15 design attributes used in the shelter evaluation studies. Detailed definitions of each design attribute are provided in Section IV.C.2. Packing ratio, weight ratio, assembly time, equipment-hours and unit cost are projected based on a database of current portable shelter attributes. This data is summarized in Section B.5. The shelter survivability attributes are based on the hardening studies presented in Section III. The survivability attributes for the upgraded shelter concepts are summarized in Section IV.D.2.

TABLE 10. CANDIDATE SMALL SHELTER CONCEPTS.

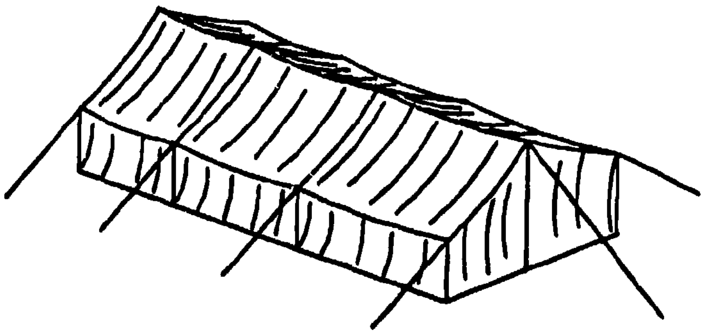
Concept	Class	Approximate Dimensions (*feet*)[a]				
		L	W_{min}	W_{max}	H_{min}	H_{max}
1. Pole-Supp. Fabric	Pole-Supp. Fabric	32	20	20	6	12
2. Frame-Supp. Fabric	Frame-Supp. Fabric	32	20	22	8	10
3. Stressed Membrane	Edge-Supp. Fabric	32	20	20	6	12
4. Air Beam Fabric	Air Beam Fabric	32	20	26	8	13
5. Dual-Wall Infl.	Air-Inflated Fabric	32	20	26	8	13
6. Air-Supp. Fabric	Air-Supp. Fabric	32	20	26	8	13
7. Accordion Box	Highly Expandable Box	40	16	16	8	8
8. Airmobile MERWS	Hybrid Panel/Frame	44	16	16	8	10
9. Hybrid MERWS	Hybrid Fabric/Panel	58	16	16	8	10
10. Geodesic Panel	Frame-Supp. Panel	32[b]	28	32[b]	8	16
11. Block Wall Shelter	Load Bearing Block Wall	32	20	20	8	10
12. Bin Wall Shelter	Load Bearing Bin Wall	32	20	20	8	10
13. Reinf. Earth Shelter	Load Bearing R/E Wall	32	20	20	8	10
14. Foam Dome Shelter	Portable Shell Struct.	32[b]	28	32[b]	8	16
15. K-Span Shelter	Portable Shell Struct.	32	20	26	8	13
16. Hypar Panel Shelter	Portable Shell Struct.	25[b]	25	25[b]	8	12

[a] W_{min} and H_{min} denote the usable shelter width and height, respectively, which define the portion of the shelter floor space that has an unobstructed vertical clearance of 8 *feet*.
[b] Base diameter.

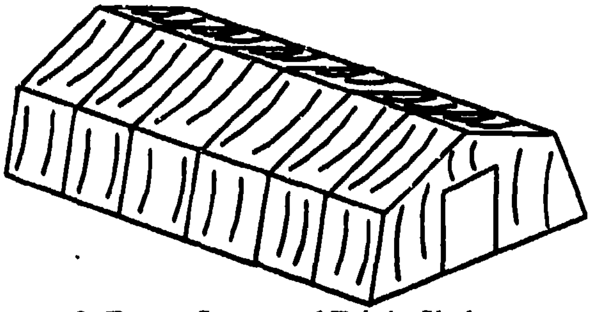
Several of the shelter cost and environmental performance attributes require more detailed design data and analyses than are available at this stage of the concept evaluation process. Therefore, based on our knowledge of current shelters, we have subjectively assigned baseline values to five of these attributes for four of the most common types of shelter construction. These estimates are listed in Table 12 and are used as reference points for the corresponding small and large shelter estimates. The remaining four shelter attributes listed in Table 8 are known characteristics of each concept. Therefore, these values are simply calculated according to the attribute definitions given in Section IV.C.2.

2. Large Span Shelters

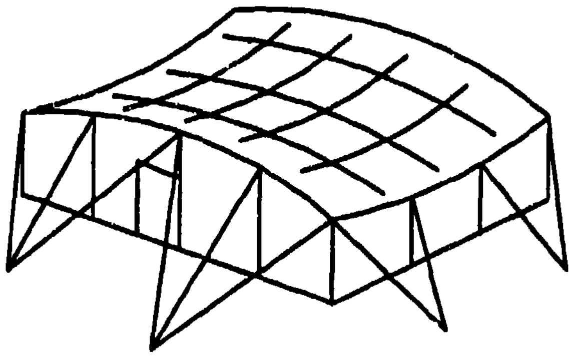
The eight candidate portable hangar concepts selected for consideration in the concept evaluation and selection task are presented in Table 13, which summarizes the shelter type and approximate dimensions for each concept. The shelters are classified according to the categories outlined in Section B. Sketches of the portable hangar design concepts are shown in Figure 35. General comments on the features of each class of portable hangar concepts are noted in Section B. Table 14 summarizes our best estimates for each of the 15 design attributes considered in the shelter evaluation study. As with the small shelter attributes listed in Table 11, the large shelter attributes are based on a combination of existing shelter data, subjective



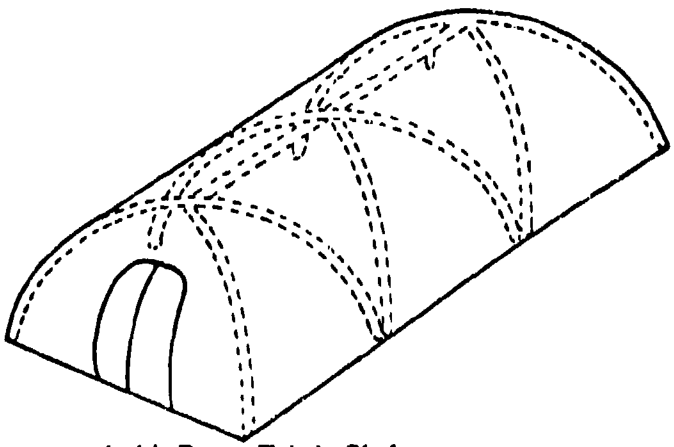
1. Pole-Supported Fabric Shelter



2. Frame-Supported Fabric Shelter

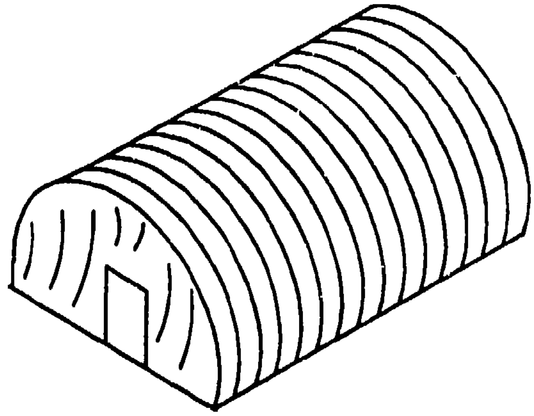


3. Stressed Membrane Edge-Supported Fabric Shelter

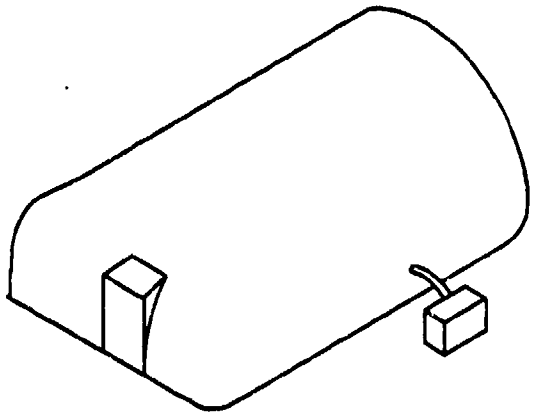


4. Air Beam Fabric Shelter

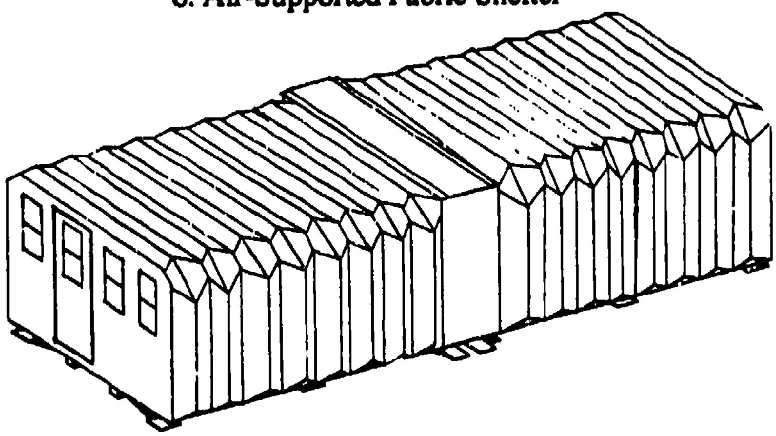
Figure 34. Small Shelter Concepts.



5. Dual Wall Inflatable Fabric Shelter

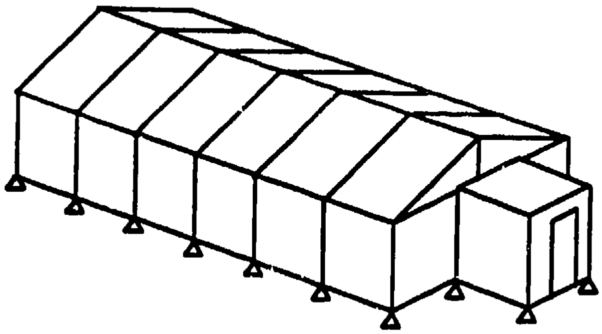


6. Air-Supported Fabric Shelter

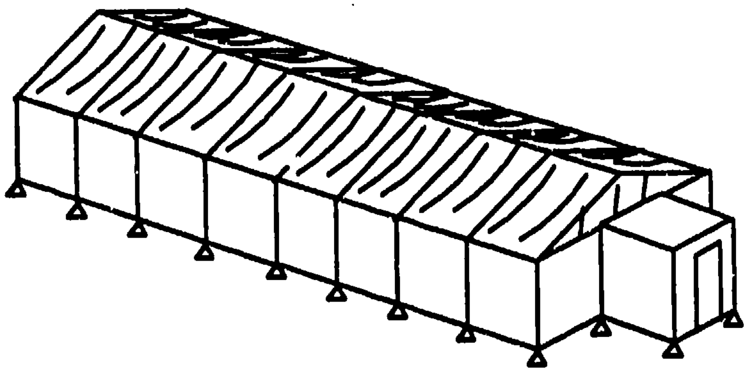


7. Accordion Box Shelter

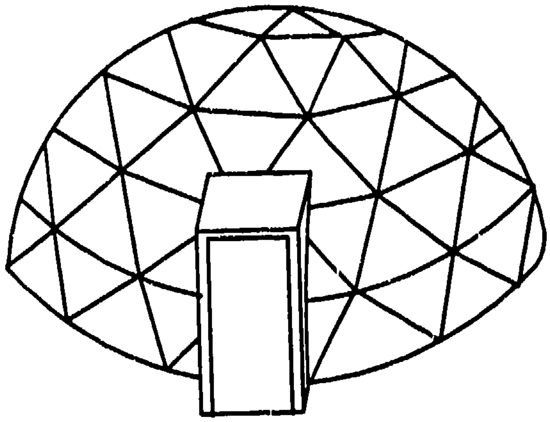
Figure 34. Small Shelter Concepts (Continued).



8. Airmobile MERWS Shelter

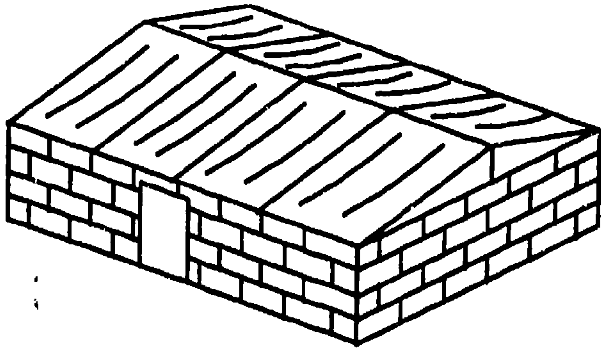


9. Hybrid MERWS Shelter

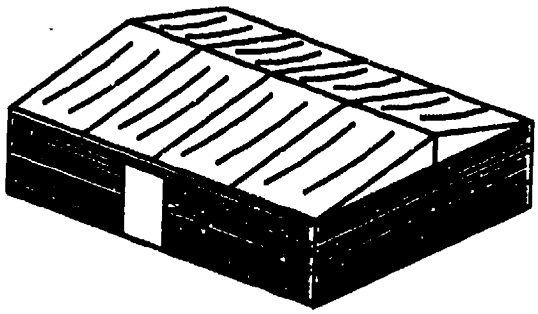


10. Geodesic Panel Shelter

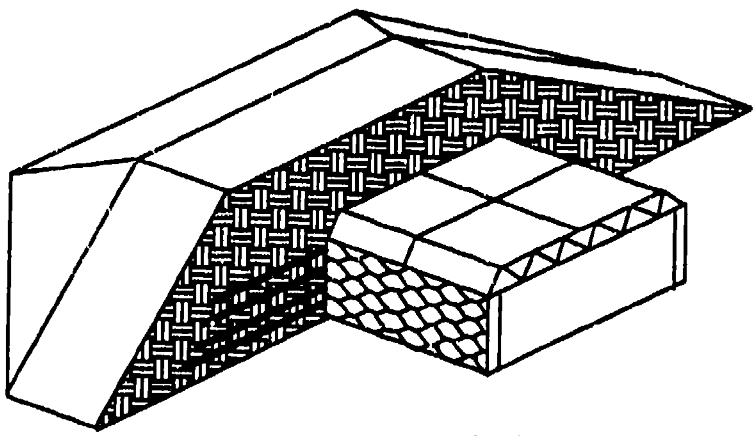
Figure 34. Small Shelter Concepts (Continued).



11. Block Wall Shelter

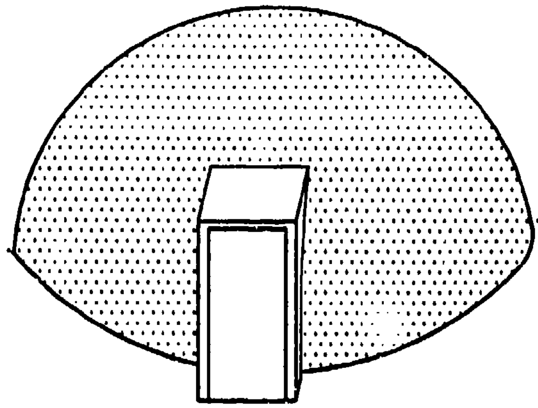


12. Bin Wall Shelter

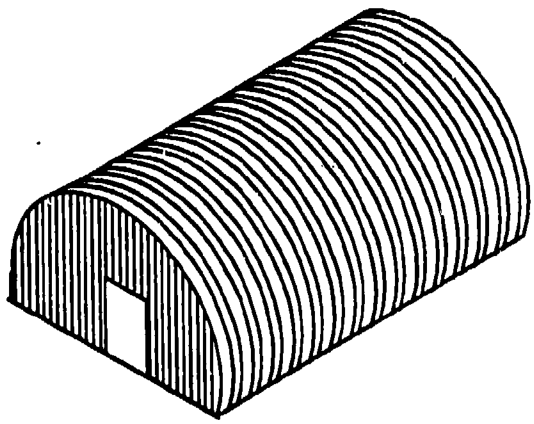


13. Reinforced Earth Shelter

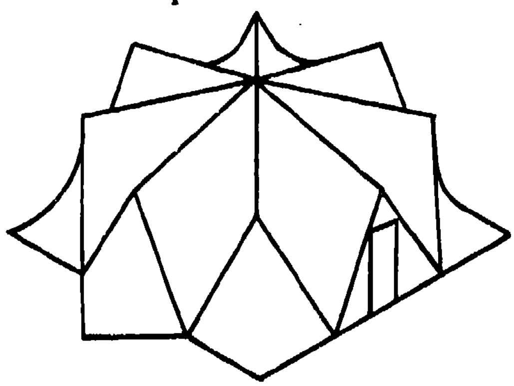
Figure 34. Small Shelter Concepts (Continued).



14. Foam Dome Shelter



15. K-Span Personnel Shelter



16. Hypar Panel Shelter

Figure 34. Small Shelter Concepts (Continued).

TABLE 11. MEDIAN DESIGN ATTRIBUTE ESTIMATES FOR THE BASIC SMALL SHELTER CONCEPTS.

Attribute	Units	Concept Number							
		1	2	3	4	5	6	7	8
Packing Ratio	*feet³/feet³*	92.37	42.23	31.99	211.13	105.57	84.45	15.83	6.81
Weight Ratio	*pounds/feet3*	0.11	0.39	0.49	0.08	0.16	0.16	0.68	1.23
Assembly Time	MH/75 *feet²*	0.35	0.94	0.94	0.35	0.70	0.47	1.41	1.27
Equipment-Hours	EH/600 *feet²*	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Unit Cost	*$/feet²*	4.69	15.63	18.75	6.25	15.63	7.81	125.00	84.75
Redepl. Cost	*Percent*	15.00	10.00	10.00	15.00	15.00	15.00	10.00	10.00
Life Cycle	# Deploy.	10.00	12.00	12.00	15.00	15.00	15.00	18.00	24.00
Floor Space	*feet²/feet²*	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.38
Volume Ratio	*feet³/feet³*	0.93	1.07	1.07	1.07	1.07	1.07	1.07	1.38
Modularity	See Text	5.00	5.00	2.00	4.00	4.00	4.00	3.00	5.00
Habitability	Hinged Doors?	no	no	no	no	no	no	yes	yes
	Rigid Floors?	no	no	no	no	no	no	yes	yes
	Rigid Walls?	no	no	no	no	no	no	yes	yes
	Rigid Roof?	no	no	no	no	no	no	yes	yes
R-Value	*Hour feet²* °F/Btu	1.00	1.00	1.00	1.00	2.00	1.00	3.00	4.00
Wind Speed	*mph*	50.00	80.00	50.00	50.00	50.00	50.00	70.00	80.00
Snow Load	*psf*	10.00	20.00	10.00	10.00	10.00	10.00	20.00	40.00
Perforation Density	#/10 *feet²*	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.57

Attribute	Units	Concept Number							
		9	10	11	12	13	14	15	16
Packing Ratio	*feet³/feet³*	8.75	10.14	42.23	21.11	10.56	60.74	42.23	10.31
Weight Ratio	*pounds/feet³*	0.92	0.61	0.49	0.59	1.17	0.61	0.49	0.72
Assembly Time	MH/75 *feet²*	1.13	3.90	3.75	3.75	7.03	1.95	2.34	2.40
Equipment-Hours	EH/600 *feet²*	0.00	0.00	3.94	3.94	7.50	0.00	0.00	0.00
Unit Cost	*$/feet²*	61.26	81.30	9.38	15.63	117.19	9.76	7.81	80.00
Redepl. Cost	*Percent*	10.00	10.00	30.00	20.00	25.00	100.00	100.00	10.00
Life Cycle	# Deploy.	21.00	18.00	12.00	8.00	6.00	1.00	1.00	18.00
Floor Space	*feet²/feet²*	1.77	1.03	1.07	1.07	1.07	1.03	1.07	1.04
Volume Ratio	*feet³/feet³*	1.77	1.03	1.07	1.07	1.07	1.03	1.07	1.04
Modularity	See Text	5.00	2.00	3.00	3.00	3.00	2.00	4.00	1.00
Habitability	Hinged Doors?	yes	yes	yes	yes	yes	yes	yes	yes
	Rigid Floors?	yes	no	no	no	no	no	no	no
	Rigid Walls?	yes	yes	yes	yes	yes	yes	yes	yes
	Rigid Roof?	no	yes	no	no	yes	yes	yes	yes
R-Value	*Hour ft²* °F/Btu	2.00	4.00	6.00	3.00	15.00	10.00	1.50	4.00
Wind Speed	*mph*	80.00	100.00	60.00	70.00	100.00	80.00	80.00	80.00
Snow Load	*psf*	20.00	40.00	20.00	20.00	40.00	30.00	30.00	40.00
Perforation Density	#/10 *feet²*	0.57	0.40	0.23	0.23	0.00	0.83	0.50	0.40

TABLE 12. BASELINE VALUES FOR SUBJECTIVELY ESTIMATED DESIGN ATTRIBUTES.

		Shelter Construction			
		Fabric		Rigid Wall	
Attribute	Units	Pole-Supported	Frame-Supported	Load-Bearing	Frame-Supported
Redepl. Cost	*Percent*	15.00	10.00	10.00	10.00
Life Cycle	# Deploy.	10.00	12.00	24.00	24.00
R-Value	*Hour feet*^{2} °F/Btu	1.00	1.00	4.00	4.00
Wind Speed	*mph*	50.00	80.00	80.00	100.00
Snow Load	*psf*	10.00	20.00	40.00	40.00

TABLE 13. CANDIDATE LARGE SHELTER CONCEPTS.

		Approximate Dimensions (*feet*)[a]				
Concept	Class	L^b	W_{min}	W_{max}	H_{min}	H_{max}
1. Frame-Supp. Fabric	Frame-Supp. Fabric	80	60	60	15	25
2. Arched Truss/Fabric	Frame-Supp. Fabric	80	62	82	15	28
3. Air Beam Hangar	Air Beam Fabric	80	62	82	15	28
4. Dual-Wall Infl.	Air-Inflated Fabric	80	62	82	15	28
5. Air-Supp. Hangar	Air-Supp. Fabric	80	62	82	15	28
6. Arch Panel Hangar	Frame-Supp. Panel	80	62	82	15	28
7. Bin Wall/Fabr. Roof	Load Bearing Bin Wall	80	60	60	15	25
8. K-Span Hangar	Portable Shell Struct.	80	62	82	15	28

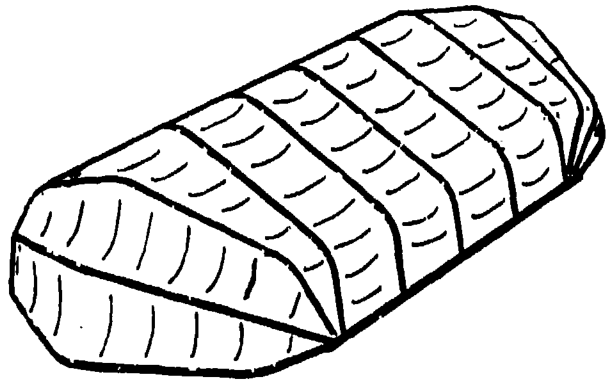
[a] W_{min} and H_{min} denote the usable shelter width and height, respectively, which define the portion of the hangar floor that has an unobstructed vertical clearance of 15 *feet*.

[b] Hangar length is measured from end-frame to end-frame (*i.e.*, increased length gained by using clamshell-type doors is not included).

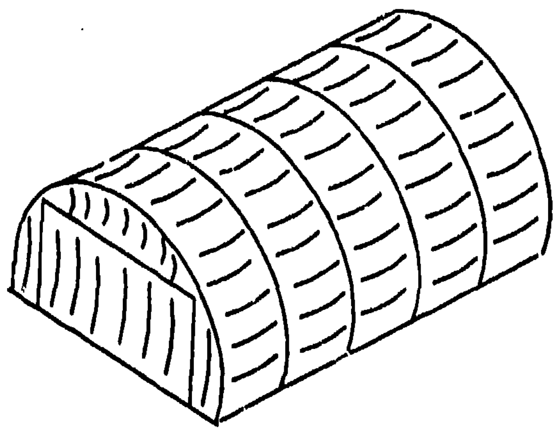
assessments based on the type of shelter construction (see Table 12), and known characteristics of the individual hangar concepts. Again, we refer the reader to Section IV.C.2 for detailed definitions of the design attributes listed in Table 14.

E. PRELIMINARY SCREENING OF SHELTER CONCEPTS

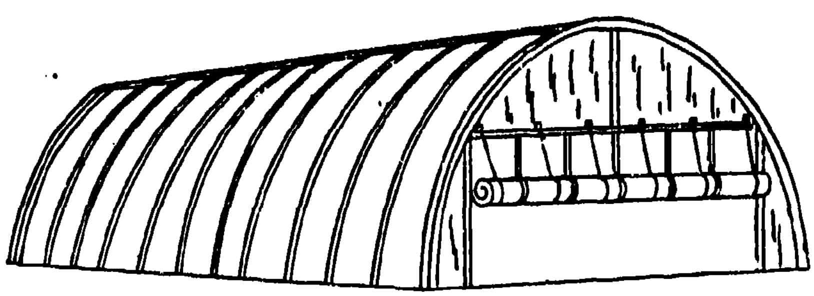
If all of the design attributes of a given shelter concept are inferior to or equal to those of another concept (with the inequality applying to at least one attribute), the latter concept is said to *dominate* the former concept. When instances of dominance are identified, three possible conclusions can be drawn: (1) the dominated concept should be eliminated from further consideration, because it is known to be inferior to at least one other alternative; (2) the list of design attributes does not cover the entire range of important design characteristics (*i.e.*, the dominated concepts has one or more positive features that are not reflected in the current set of design attributes); or (3) the uncertainties in the estimated values of the design attributes may be large enough to warrant the inclusion of marginally dominated concepts.



1. Frame-Supported Fabric Hangar

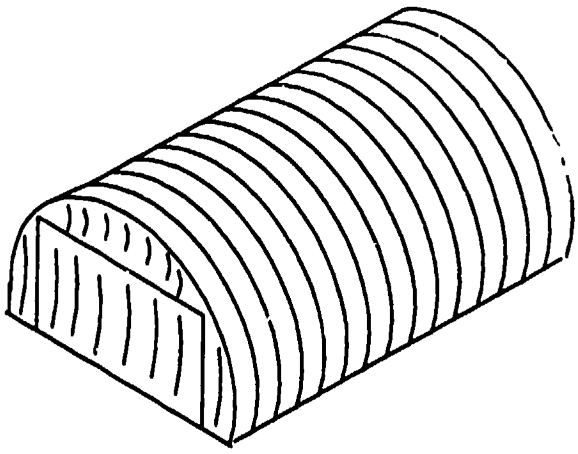


2. Arched Truss-Supported Fabric Hangar

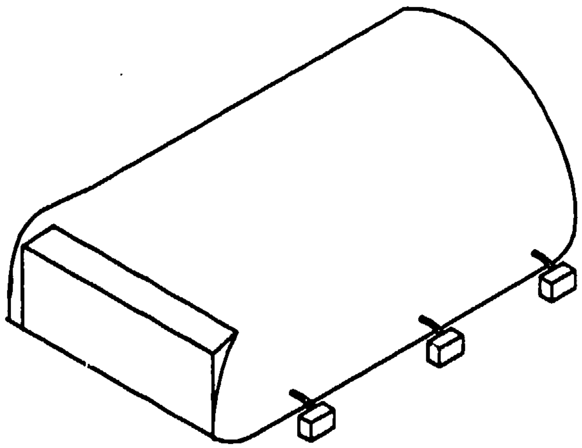


3. Air Beam-Supported Hangar

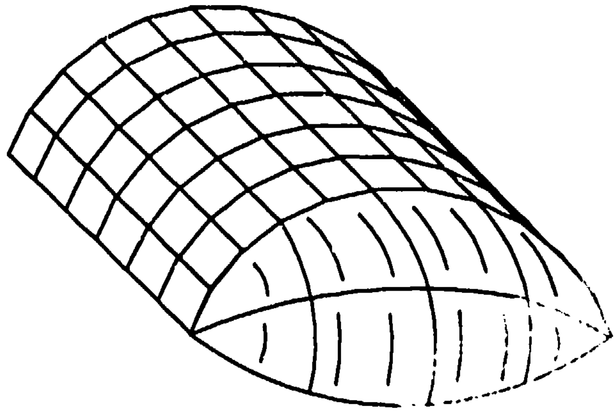
Figure 35. Large Shelter Concepts.



4. Dual Wall Inflatable Hangar

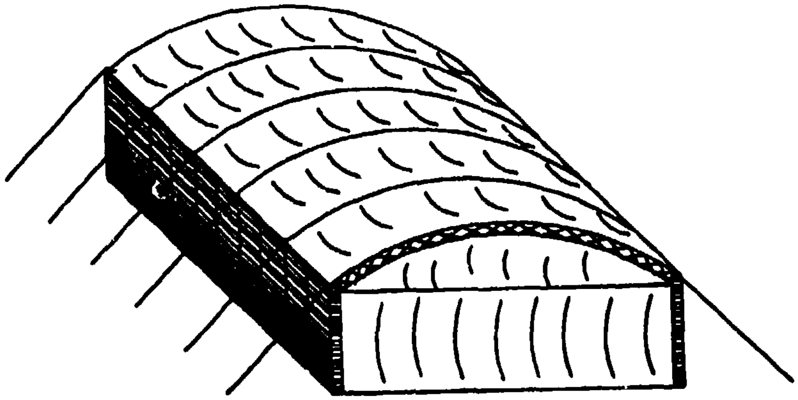


5. Air-Supported Fabric Hangar

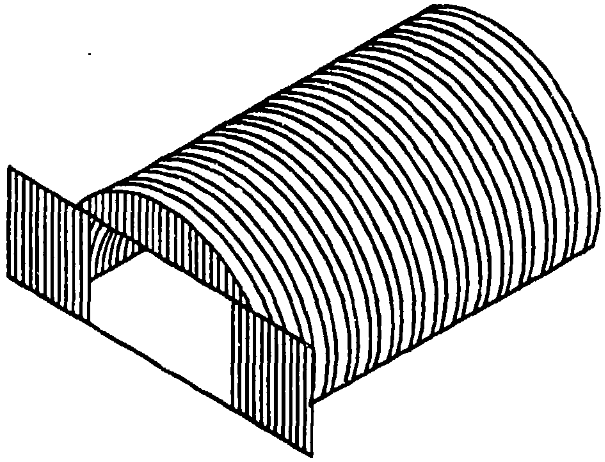


6. Arch-Supported Panel Hangar

Figure 35. Large Shelter Concepts (Continued).



7. Bin-Wall/Fabric Roof Hangar



8. K-Span Hangar

Figure 35. Large Shelter Concepts (Continued).

Before proceeding to the hardening trade studies and shelter evaluation studies in Sections III and IV, it is appropriate to check each of the small and large shelter concepts for dominance. Since we will develop a standard set of shelter-hardening upgrades in Section III and most of these upgrades will be equally applicable to each design concept, we shall specifically exclude shelter survivability from this preliminary screening exercise. Because we are intentionally omitting a key group of shelter design attributes, a dominated concept will not be eliminated at this point unless it is clear that it will also be dominated with respect to survivability as well. Finally, given the uncertainty in estimating many of the design attributes, it may be necessary to retain concepts that are only marginally dominated.

1. Small Shelter Concepts

After considering all possible pairs of basic (*i.e.*, nonupgraded) small shelter concepts, we have identified only two cases of dominance. The attributes of the air beam concept meet or exceed every attribute of the air-supported shelter concept, and the frame-supported fabric shelter concept dominates the stressed membrane edge-supported fabric shelter concept. However, in most instances the attributes are equal. For the air beam and air-supported shelters, the median estimates for packing ratio, weight ratio, man-hours, and unit cost are the only cases in which the air beam outperforms the air-supported shelter (Table 14). Since we have not identified any current or developmental air-supported shelters, there is a greater than average degree of uncertainty in the air-supported shelter attribute estimates. Therefore, we have elected to retain the air-supported shelter in the concept evaluation studies even though we know that it will rank lower than the air beam concept. Similarly, the stressed membrane concept is not strongly dominated by the frame-supported fabric shelter. Furthermore, the stressed membrane concept is not currently in use; therefore, there is also significant uncertainty associated with many of its attributes. Hence, we will also retain the stressed membrane concept for our detailed shelter evaluations in Section IV.

2. Large Shelter Concepts

Among the eight candidate portable hangar concepts, there is one instance of dominance in the basic, unhardened configurations. As with their small shelter counterparts, the air beam hangar concept dominates the air-supported hangar concept. Based on the same reasoning used for the small shelters, we will retain the air-supported hangar for the concept evaluation and selection results to be presented in Section IV.

TABLE 14. MEDIAN DESIGN ATTRIBUTE ESTIMATES FOR THE BASIC LARGE SHELTER CONCEPTS.

Attribute	Units	Concept Number							
		1	2	3	4	5	6	7	8
Packing Ratio	$feet^3/feet^3$	98.97	102.27	306.80	153.40	228.96	43.83	59.38	21.91
Weight Ratio	*pounds/feet3*	0.10	0.09	0.07	0.11	0.10	0.41	0.21	0.94
Man-Hours	MH/75 $feet^2$	0.94	0.91	0.39	0.73	0.60	1.51	1.56	2.27
Equipment-Hours	EH/600 $feet^2$	0.00	0.00	0.00	0.00	0.00	0.00	2.63	1.94
Unit Cost	\$/$feet^2$	10.42	10.08	8.06	12.10	14.11	100.81	20.83	8.06
Redepl. Cost	*Percent*	10.00	10.00	10.00	10.00	10.00	10.00	20.00	100.00
Life Cycle	# Deploy.	12.00	12.00	15.00	15.00	15.00	24.00	10.00	1.00
Floor Space	$feet^2/feet^2$	1.00	1.03	1.03	1.03	1.03	1.03	1.00	1.03
Volume Ratio	$feet^3/feet^3$	1.00	1.03	1.03	1.03	1.03	1.03	1.00	1.03
Modularity	See Text	5.00	4.00	4.00	4.00	4.00	5.00	5.00	4.00
Habitability	Hinged Doors?	no	no	no	no	no	yes	yes	yes
	Rigid Floor?	no	no	no	no	no	no	no	no
	Rigid Walls?	no	no	no	no	no	yes	yes	yes
	Rigid Roof?	no	no	no	no	no	yes	no	yes
R-Value	*Hour* $feet^2$ °F/Btu	1.00	1.00	1.00	2.00	1.00	4.00	3.00	1.50
Wind Speed	*mph*	80.00	80.00	50.00	50.00	50.00	100.00	80.00	80.00
Snow Load	*psf*	20.00	20.00	10.00	10.00	10.00	40.00	20.00	30.00
Perforation Density	#/10 $feet^2$	0.69	0.69	0.69	0.69	0.69	0.43	0.18	0.35

SECTION III

HARDENING ASSESSMENT

A. INTRODUCTION

A primary goal of the airmobile shelter development program is the integration of hardening into the new family of shelters. SON and ORD hardening objectives are at least Splinter Protection for personnel billeting and low value targets and up to Semihardened for high value targets such as command and control centers, and aircraft shelters. The basic assumption behind these objectives is that these levels of protection may be attainable at reasonable cost and weight through the use of modern composite materials.

Establishing the validity of the assumption that Splinter or Semihardened levels of protection are feasible in lightweight airmobile shelters is a primary driver in the FOPS research and development. Consequently, a major portion of the current research focused on evaluating the feasibility of hardening FOPS. Specifically, our research sought answers to the following questions:

1. Are Splinter and Semihardened levels of protection feasible for FOPS using modern ballistic composites?
2. If Splinter and Semihardened levels of protection are not feasible, are modern ballistic composites effective protecting against small anti-personnel munitions?
3. How does the effectiveness of integral shelter hardening methods compare to that of expedient hardening methods?
4. Is integral, upgradeable, or expedient hardening the preferred approach for FOPS?

The resolution of these questions required a review of related threat documents to identify and characterize conventional munitions that present a threat to FOPS, development of hardening concepts to defeat these threats, and the development of analysis models to evaluate the effectiveness of these hardening concepts against the fragment and airblast loads produced by the selected munitions. In the following subsections, we present the results of our analyses. Section III.B reviews conventional munitions that present a threat to airbases and selects six representative munitions for analysis. Section III.C discusses potential hardening methods. Sections III.D and III.E present preliminary assessments of the airblast and small arms protection afforded by modern composites. In Section III.F, we develop an analysis procedure for assessing the effectiveness of hardening upgrades against the fragment effects of munitions, and use this model in Section III.G to evaluate alternative hardening approaches for fragment protection.

B. THREAT

The threats of Splinter, Exposure, Collateral, and Semihardened consider four classes of weapons at various standoffs: (1) GP bombs, (2) air-to-surface missiles, (3) air-to-surface rockets, and (4) aircraft cannon fire. These weapon threats are typical of air delivered munitions against fixed, permanent facilities. As demonstrated in our analyses, the GP bomb is typically the controlling threat for these weapon groups. Early scoping studies indicated that providing Splinter Protection and Semihardened Protection against the large, high velocity fragments generated by GP bombs is probably not feasible in a lightweight shelter, even with modern lightweight, ballistic composite materials. However, it is equally evident that these materials can significantly enhance survivability against less severe threats.

To supplement the SON and ORD threat objectives, a review of threat related documents [Air Force, 1991 and ND; Materials Technology Laboratory (MTL), 1990] was conducted and discussions were held with various user agencies and threat experts. Battlefield threats are governed by the nature of the conflict, terrain, and mission of the user agency in the conflict. Consequently, our survey results showed a wide diversity in user perceived threats. Bare base deployments are typically well behind the front lines and assume U.S. air superiority; hence, hardening is normally a secondary consideration for bare base applications. Bare base deployments in Saudi Arabia (1991) during DESERT STORM reinforce this perception due to the clear air superiority enjoyed by coalition forces and the failure of the enemy to bring the war to coalition forces. However, threats are not negligible for all scenarios. The NATO air base survivability and operability criteria [NATO STANAG 2929] consider the threat of surface and penetrator bombs, fragmentation bomblets, scatter mines, and chemical agents aimed at disrupting operations and denying use of NATO airbases [Christensen, *et al.*, 1982]. With current land restrictions, these munitions would pose a threat to nearby personnel billeting and operations shelters as well as aircraft maintenance shelters. In Vietnam, the lack of a clearly defined front, mobility of opposing forces, and dense foliage resulted in U.S. air bases being subjected to extensive small arms fire and man-portable fragmenting munitions.

Under the current Air Force policy of Global Reach/Global Power, future deployments will involve a variety of deployment scenarios and corresponding threats, including bare base deployment in relatively benign environments (*e.g.*, DESERT STORM), deployment of military airlift support in ethnic/nationalistic confrontations in Europe (*e.g.*, the breakup of Yugoslavia during 1992), and counterinsurgency efforts in Africa and Central America. Available stocks of ammunition and munitions in probable regions of conflict are skewed towards conventional, close combat type munitions [MTL, 1990]; consequently, the threat faced by these deployments can be expected to be heavily weighted towards small arms and small fragmenting munitions such as mortars and artillery. Targeting of personnel and materiel with cluster munitions, chemical/biological weapons, and fuel air explosives (FAE) can also be expected [Air Force, 1991].

The review of related threat documents and user discussions suggests that FOPS should be evaluated against a spectrum of weapons, ranging from small arms up to GP bombs. Representative weapon groups include: (1) small arms (pistols, rifles, and machine-guns); (2) aircraft cannons; (3) small fragmenting munitions (mortars and artillery); (4) cluster munitions; (5) air delivered weapons (rockets, missiles, and bombs); (6) chemical/biological munitions; and (7) fuel air explosives (FAE). These weapon threats can be further grouped for analysis according to primary weapon effect: (1) ballistic (small arms); (2) fragment impact (artillery, mortars, rockets, missiles, and bombs); (3) airblast (rockets, missiles, bombs and FAE); and (4) chemical/biological (all modes of delivery). Chemical/biological protection is engineered through careful material selection and design of the shelter cladding system and HVAC system. This level of design detail is beyond the scope of the present study; hence, CB protection was not considered in this assessment. As will be demonstrated in our analysis, fragmentation is the controlling weapon effect for feasible protection levels for FOPS. Consequently, the hardening analyses focused on fragment impact and only preliminary scoping calculations were performed for small arms fire and airblast effects.

1. Ballistic Small Arms

Small arms weapons include pistols, assault rifles, light machine-guns and submachine-guns. Projectiles may be lead or steel core, and typically range in diameter from 5.5 *mm* up to 12 *mm*. Typical projectile diameters and muzzle velocities are summarized in Table 15. Impact velocities are a function of projectile size and weapon standoff. Typical range-velocity curves for small arms projectiles are shown in Figures 36 and 37.

At the simplest level, small arms protection is provided by placing a sufficient mass of material (*e.g.*, soil cover) between the source and target. This mass is typically stated in terms of thickness or areal density (weight per unit surface area). As materials become more efficient (for example, ballistic composite and steel armors) in resisting penetration, lower areal densities of material are required. Impact velocities for small arms projectiles are much lower than those for larger fragmenting munitions; hence, small arms protection can be provided at significantly lower areal densities than fragment protection (see Section III.E).

TABLE 15. SMALL ARMS PROJECTILE SIZES AND MUZZLE VELOCITIES.

Projectile Diameter *mm* (*in*)	Projectile Weight *grains*	Muzzle Velocity *m/s*	Muzzle Velocity (*fps*)
5.56 (0.22)	43 - 56	800 - 1000	(2600 - 3300)
7.62 (0.30)	74 - 106	300 - 900	(1000 - 2900)
9.0 (0.35)	125 - 160	300 - 440	(1000 - 1450)
11.5 (0.45)	208 - 234	250 - 300	(800 - 1000)

2. Fragment Impact

The primary threat to personnel, lightly armored vehicles, and transportable shelters is fragmentation from nearby detonation of fragmenting munitions. Approximately two-thirds of all personnel casualties in World II, Korea, and Vietnam have been attributed to use of small fragmenting munitions [MTL, 1990]. Small fragmenting munitions include artillery, mortars, aircraft cannon projectiles, and cluster bomblets. These munitions are typically optimized for antipersonnel and anti-materiel fragmentation and generate thousands of small, high speed fragments. In addition to these small fragmenting munitions, shelter hardening must consider collateral fragment damage from rockets, missiles, and GP bombs targeted against nearby high value targets.

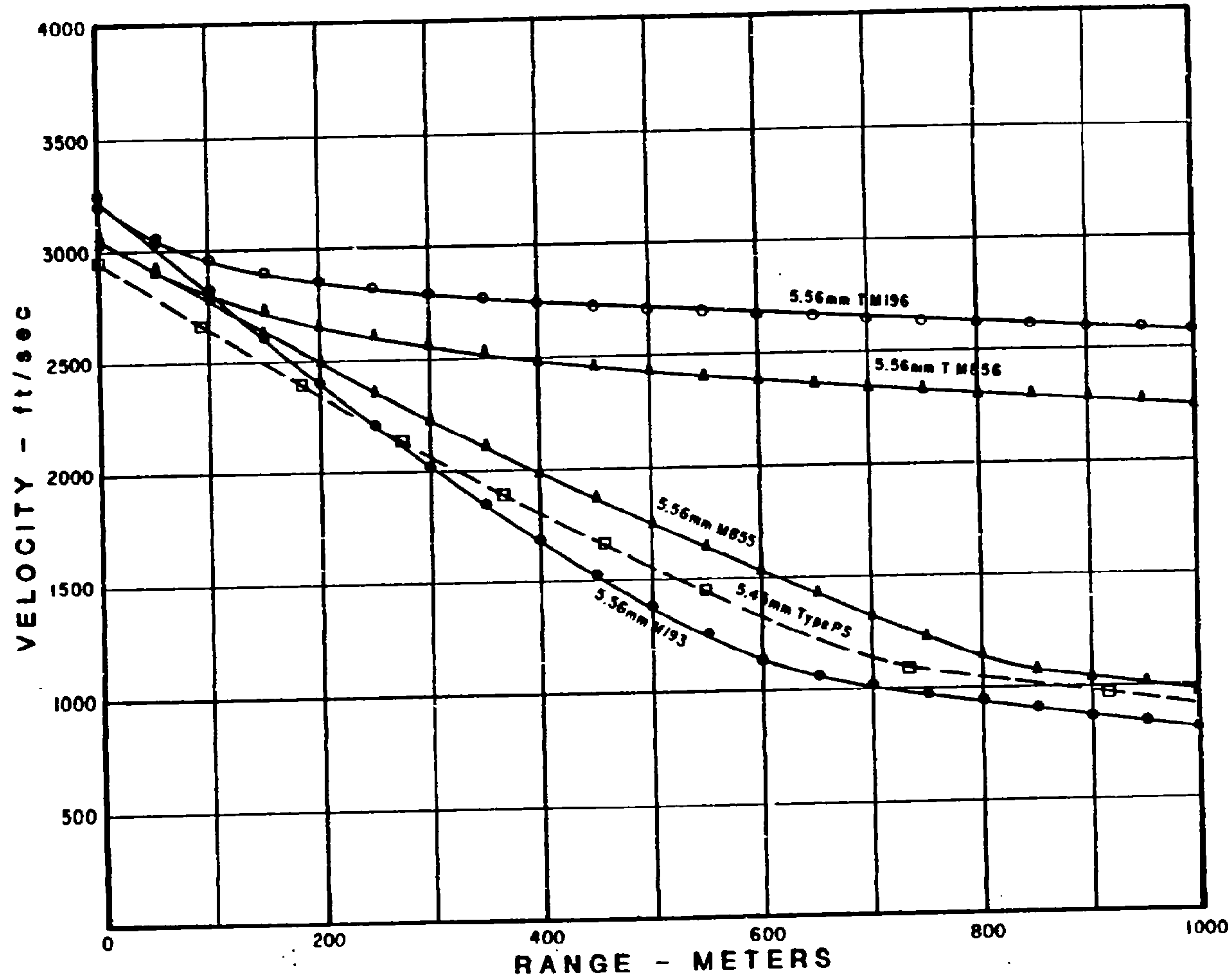


Figure 36. Range-Velocity Curves for 5.45/5.56-mm Small Arms Ammunition [MTL, 1990].

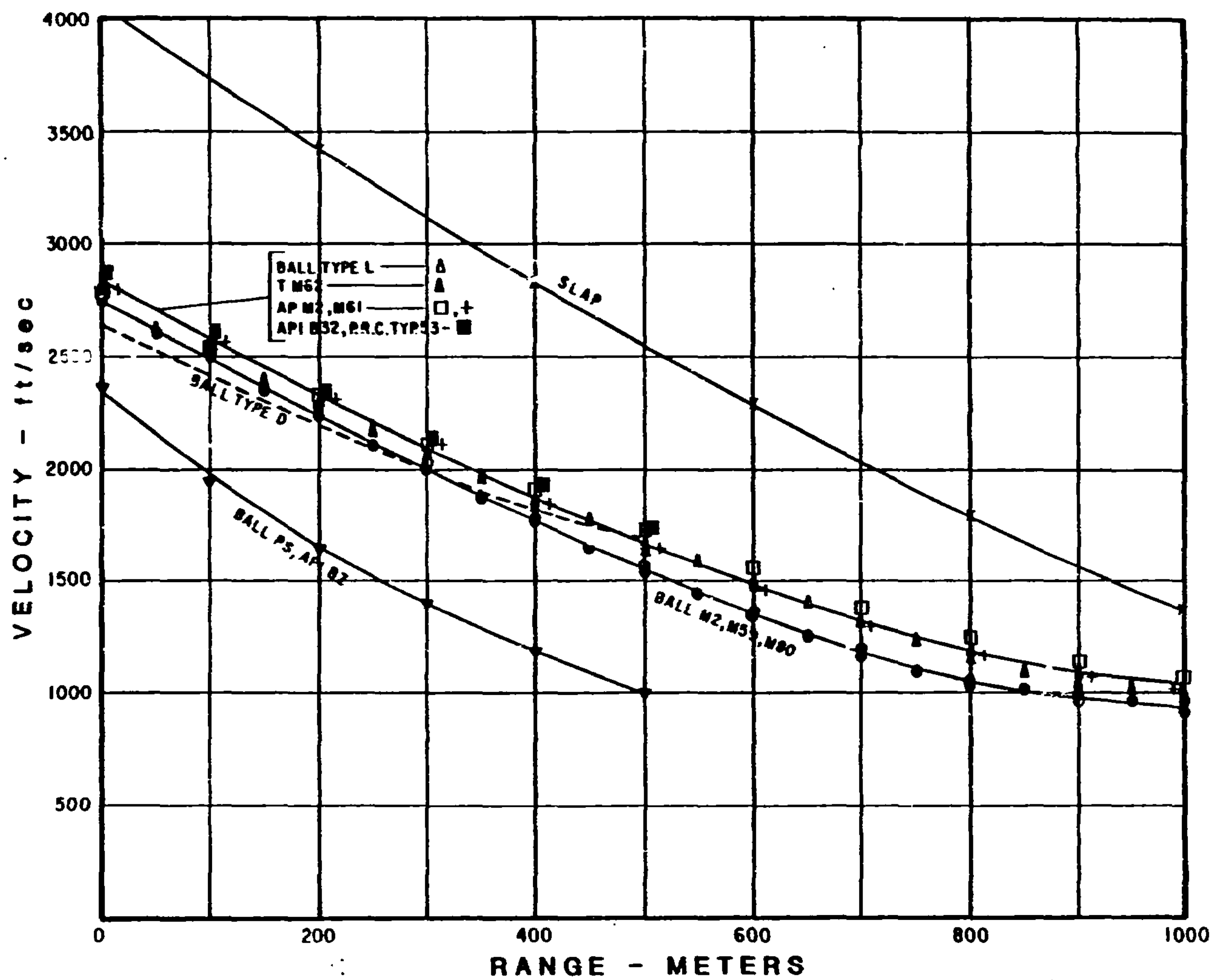


Figure 37. Range-Velocity Curves for 7.62-*mm* Small Arms Ammunition [MTL, 1990].

As with small arms fire, protection against fragment impact is accomplished by providing a sufficient areal density of ballistic material to stop the fragment. Protection against fragment impact is further complicated by the wide range of fragment sizes, shapes, masses, and impact velocities generated by a single weapon detonation. Figures 38 through 40 plot typical fragment weight distributions for the various classes of fragmenting munitions. These cumulative distributions plot the fraction of the total number of fragments with weights equal to or lighter than the weights shown on the axis. The distributions are based on parameters tabulated in the *PCDM*. For example, approximately 80 *percent* of the fragments produced by a 60-*mm* U.S. mortar shell weigh 10 *grains* or less (Figure 38). Examination of these figures shows that the fragment distributions produced by the various classes of weapons are similar, with the major difference being in the number of fragments and initial fragment velocity, as shown in Figure 41. A short cursory discussion of weapon characteristics relevant to the shelter hardening assessment follows.

a. Aircraft Gun Ammunition

Typical aircraft ammunition range in bore from 20-*mm* to 40-*mm*. Projectiles may be high explosive (HE), high explosive/incendiary (HEI), high explosive/incendiary tracer (HEIT), or armor piercing (AP). Figure 42 shows mean fragment weights and initial fragment velocities for HE and HEI rounds [Drake, *et al.*, 1989; JTCG, 1989, 1992]. HE and HEIT rounds typically generate fragments on the order of 1 to 20 *grains* with mean fragment weights of a few grains. Initial fragment velocities are typically between 2 and 4 *kfps* (*kilo-feet per second*). The small fragment weights and low initial fragment velocities generated by aircraft gun ammunition can be stopped by relatively small areal densities of composite armors.

b. Cluster Munitions

Cluster munitions are small grenade-like anti-personnel and anti-materiel submunitions optimized to produce thousands of small, high-speed fragments. Casings for these submunitions are typically scored or embossed to provide controlled fragmentation. Reflectance fracture and cast spheres or cubes may also be used for fragment control. As such, fragment weight distributions are typically very narrow with mean fragment weights typically on the order of 1 to 20 *grains* with initial fragment velocities in the range of 2500 to 5600 *fps*. Cluster submunitions are delivered using artillery, air-surface rockets and missiles, and special purpose bomb pods [JTCG, 1992].

c. Mortar and Artillery Projectiles

Table 16 summarizes typical weapon characteristics for mortar and artillery projectiles. The high-explosive content of these projectiles is typically 15 to 25 *percent* of the total projectile weight, which is sufficient to cause severe blast and fragmentation effects when detonated at small standoffs. HE, HEAT, AP, and RAP (rocket-assisted projectiles)

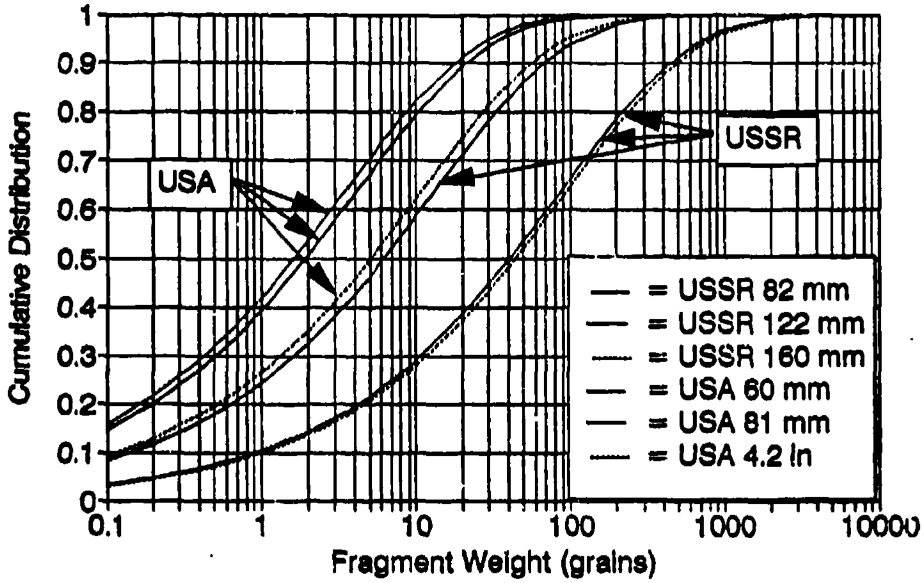


Figure 38. Fragment Weight Distribution for U.S. and Soviet Mortar Shells [adapted from Drake, *et al.*, 1989].

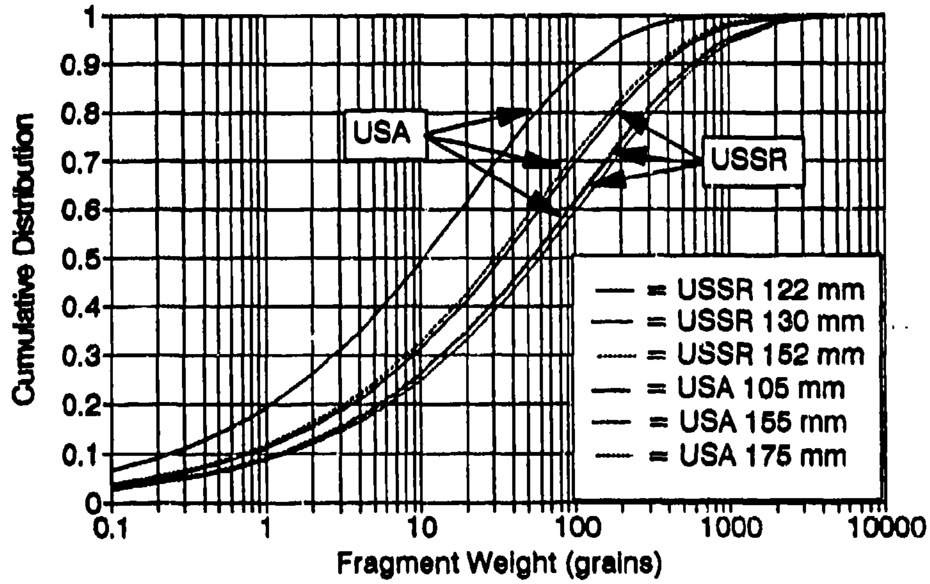


Figure 39. Fragment Weight Distributions for U.S. and Soviet Artillery Shells [adapted from Drake, *et al.*, 1989].

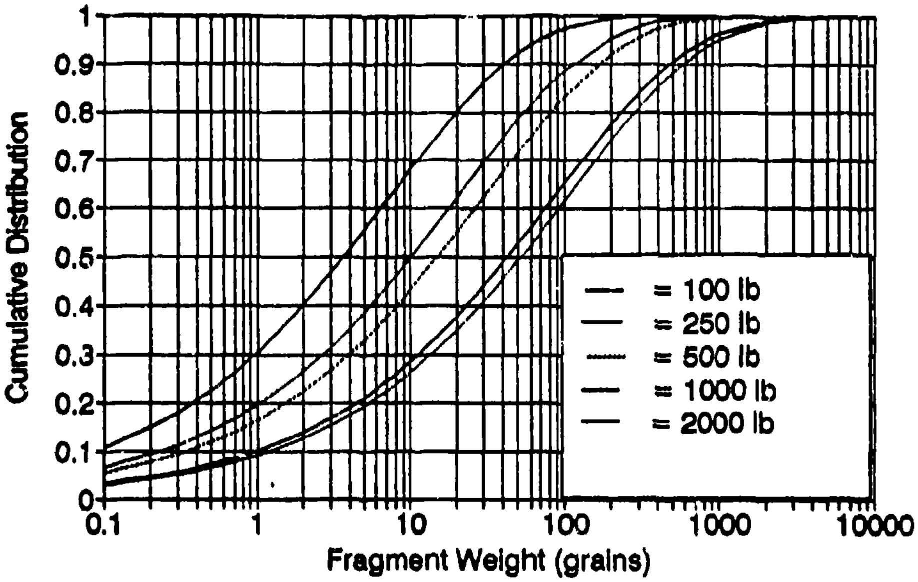


Figure 40. Fragment Weight Distributions for U.S. General Purpose Bombs [adapted from Drake, *et al.*, 1989].

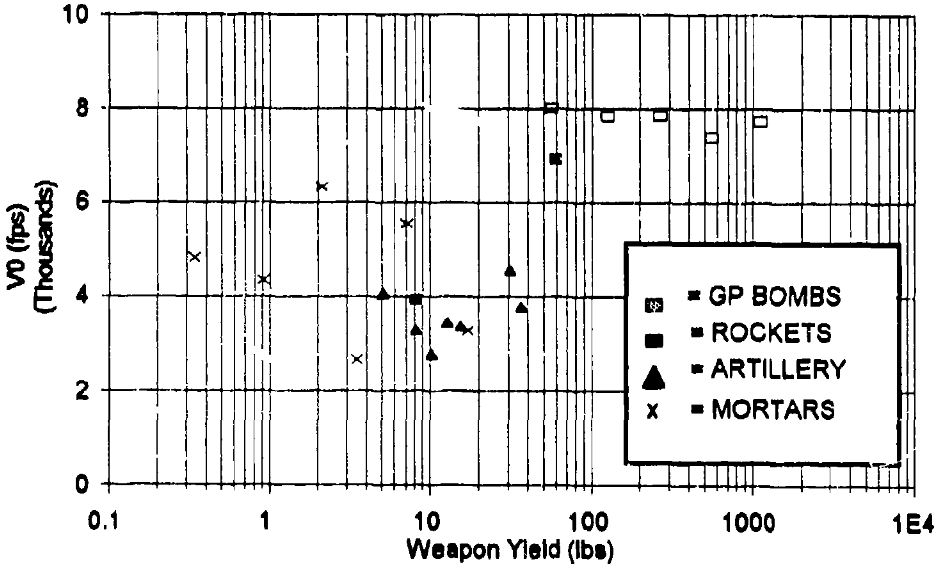


Figure 41. Number of Fragments and Initial Fragment Velocity for Fragmenting Munitions [adapted from Drake, *et al.*, 1989].

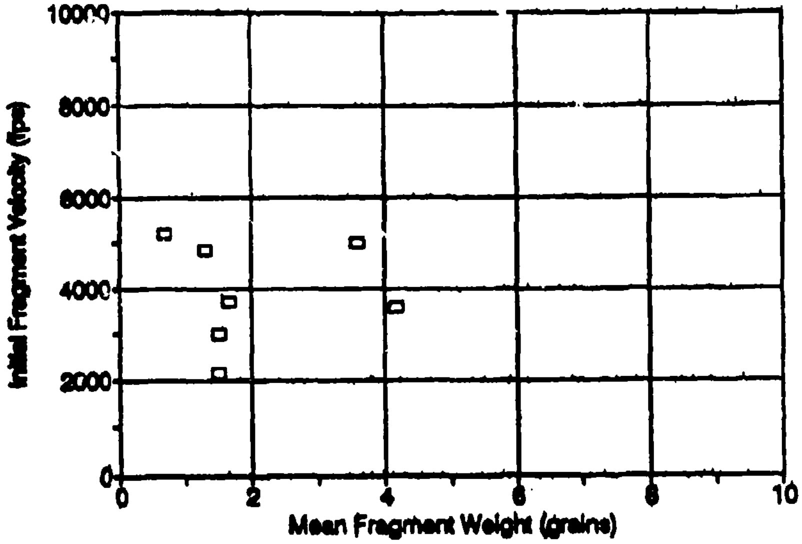


Figure 42. Typical Mean Fragment Weights and Initial Velocities for Aircraft Gun Rounds.

TABLE 16. FRAGMENT AND WEAPON CHARACTERISTICS FOR MORTAR AND ARTILLERY PROJECTILES.

Projectile Caliber (*mm*)	Projectile Velocity (*fps*)	Projectile Range (*feet*)	Projectile Total Weight (*pounds*)	Explosive Weight Fraction W_e/W_t	Mott's Constant (*pounds*$^{1/2}$)	Number of Fragments N_f	Initial Velocity (*fps*)
Mortars							
60	520	6,000	3.2	0.11	0.024	2,500	4,820
81/82	7-900	10-15,000	6.8-9.4	0.13-0.22	0.022-.043	2,200-5,500	4,300-6,300
106	970	18,500	27	0.26	0.039	6,600	5,550
120	890	18,700	35	0.11	0.110	1,300	2,660
160	1,130	26,400	91	0.19	0.115	1,000	3,280
240	1,190	31,800	288	0.24	-	-	-
Artillery							
105	1,600	37,700	33	0.15	0.056	4,500	4,060
122	3,000	71,800	48	0.17	0.101	2,000	3,300
130	3,100	102,000	74	0.14	0.133	1,800	2,780
152/155	2,000	48-57,000	95	0.13-0.16	0.125	2,600	3,400
175	3,000	107,300	147	0.21	0.096	6,300	4,550
180	2,600	98,400	225	-	-	-	-
203	2,000	55-58,000	200-220	0.15-0.18	-	-	-

modifications are available. Contact-fused HE projectiles are very effective in exposed anti-personnel/equipment applications. Projectiles range in size from 60 *mm* to 200 *mm* with ranges of 3 to 6 *miles* for mortars and 7 to 20 *miles* for artillery. As illustrated in Figures 38, 39 and 41 and Table 16, Soviet munitions tend to produce heavier fragments, but with lower initial fragment velocities [Drake, *et al.*, 1989].

d. Rockets and Missiles.

Rockets and missiles are designed primarily for use against armored vehicles and other hard targets; however, alternative warheads are available which are effective against personnel, equipment, and lightly armored vehicles and shelters. Rockets range in bore size from 66 to 240 *mm* with weights ranging from 2 to 60 *pounds*. Rockets are typically launched from multitube launchers and have an unguided boost phase followed by a ballistic flight phase. Available warheads include: (1) HE, (2) shaped charge, (3) HE-FRAG with performed cubic fragments, (4) flechette-loaded, (5) submunition dispensing, and (6) smoke/chaff [JTCG, 1992; Drake, *et al.*, 1989].

Missiles are typically guided, longer range, and larger than their rocket counterparts. They are typically anti-radiation (ARM) and their primary targets are radar sites and other electromagnetic radiating targets, such as those associated with surface-to-air missiles (SAM) and anti-aircraft sites. Warheads typically weigh from 100 to 300 *pounds* with total missile launch weights in excess of 1000 *pounds*. They can reliably and accurately deliver HE amounts comparable to that contained in bombs from sites located hundred of miles from the target [JTCG, 1992, Drake, *et al.*, 1989].

e. High-Explosive (HE) Bombs

HE bombs include all bomb types containing HE material for blast and fragmentation: (1) GP — general purpose, (2) LC — light case, (3) FRAG — fragmentation, (4) AP — armor piercing, and (5) FAE — fuel-air-explosive bombs. Of these, the GP and FRAG are the greatest fragmentation threat to airbase structures. GP bombs are the most common and are designed to cause blast and fragmentation damage from above-surface explosions, or ground shock and cratering damage from buried explosions. They can be proximity (air burst), contact (surface burst), or delayed (buried burst) fused. Table 17 summarizes typical weapon and fragment characteristics for GP bombs. Fragmentation (FRAG) bombs are designed for controlled fragmentation against personnel and lightly protected materiel. They have a low charge-to-weight ratio; hence, blast damage from these munitions is minimal in comparison to GP bombs [Drake, *et al.*, 1989].

3. Airblast

In addition to their fragmentation threat, the weapons discussed in the previous section present an airblast threat due to their high-explosive content. Charge and casing weights,

TABLE 17. FRAGMENT AND WEAPON CHARACTERISTICS FOR GENERAL PURPOSE BOMBS [Drake, *et al.*, 1989].

Bomb	Total Weight (*pounds*)	Diameter (*in*)	Length	Charge Weight Ratio	Mott's Constant (*pounds*$^{1/2}$)	No. of Fragments N_f	Initial Velocity (*fps*)
GP-100 *pound*	110	8	29	.51	0.033	24,700	8,030
GP-250 *pound*	260	11	36	.48	0.055	22,300	7,860
GP-500 *pound*	520	14	45	.51	0.067	28,400	7,880
GP-1000 *pound*	1020	19	53	.54	0.113	18,400	7,410
GP-2000 *pound*	2090	23	70	.53	0.125	31,400	7,760

where available, were summarized in the corresponding tables on weapon characteristics. These properties can be used in analytical equations, such as those contained in the *PCDM* to calculate the blast pressures on the shelter surface. The relative importance of airblast effects with respect to the fragment threat will increase with decreasing standoff. For the larger weapons, such as bombs and the larger missiles, the combination of the airblast loading on the shelter wall and fragment impacts will most likely make shelter hardening unfeasible at small standoffs. For the smaller weapons, such as aircraft gun ammunition and cluster munitions, airblast effects are not expected to be important.

Fuel air explosive (FAE) munitions also present a threat to air base structures. In general, FAE munitions disperse a fuel vapor cloud over a wide area, and, after an appropriate delay, detonate a small high-explosive charge. Detonation of this charge initiates combustion in the surrounding fuel-vapor cloud, generating overpressures on the order of 250-350 *psi* within the cloud. The combined overpressure and impulse provide the damage mechanism for surface targets. Since FAE munition are designed such that the fuel vapor cloud extends down to the ground surface, any structure within this region would be subjected to the overpressure and impulse within the cloud. Lightweight airmobile shelters cannot be designed to withstand the blast pressures expected to occur within the fuel-vapor cloud; hardening must be provided by mounding the shelters to attenuate the blast pressure.

4. Summary

In conclusion, weapon threats for portable airbase structures span the spectrum of conventional and nonconventional weapons, including small arms; air-to-surface, surface-to-surface, and manportable rockets; mortars and artillery; aircraft cannon fire; air-to-surface and surface-to-surface missiles; and air delivered bombs. To provide a robust evaluation of the potential for hardening the new family of airmobile shelters, we have selected six representative weapons that provided a range of airblast and fragmentation threats. These weapons include the four standard threat weapons: (1) 40-*mm* aircraft cannon fire; (2) 122-*mm* rocket; (3) 250-*pound* missile; and (4) 1000-*pound* bomb. To these weapon threats we have added 152/155-*mm* artillery shell and cluster munitions. The 152/155-*mm* artillery shell is a common weapon threat for lightly armored vehicles while cluster munitions, with their antipersonnel/anti-materiel design, would be a likely weapon choice for attacking personnel billeting and lightly protected facilities.

C. SHELTER HARDENING METHODS

In this section, we present several potential approaches that may be suitable for the new FOPS. The primary threat, as we have previously discussed in Section III.B and will demonstrate in Sections III.D through III.G, is perforation of the shelter walls by fragments from nearby weapon detonations. To achieve ballistic hardening against fragment perforation, sufficient areal density (mass) of material must be placed between the fragment source and shelter to stop the fragments. This mass can be expediently provided simply by mounding soil around the perimeter of the shelter to intercept and stop the fragments. On a more efficient basis, ballistic materials can be integrated into the shelter design or applied as liners/shields to upgrade the shelter hardness.

In the discussion that follows, we will divide potential hardening upgrades into three basic categories: (1) integral hardness, (2) field installable upgrades, and (3) field expedient upgrades. Our primary interest is in integral hardness and field installable upgrades that are portable and cost-effective. Field expedient upgrades provide proven low cost alternatives for evaluating the effectiveness of the integral and field installable upgrades.

1. Integral Hardness

Integral hardness is the inherent hardness of the basic shelter against conventional weapon effects. An airmobile shelter may have zero hardness, as represented by current fabric shelters (*e.g.*, tents), or it may have some limited hardness, as represented by current tactical shelters. Integral hardness can be provided in these shelters by replacing shelter materials with modern ballistic fabrics and composite materials. This hardness may be incorporated as an integral part of the basic shelter design (*i.e.*, all shelters are hardened to this level) or may be incorporated through the use of interchangeable components to selectively harden individual shelters. For fabric shelters (*e.g.*, the TEMPER tent) integral hardness can be provided by replacing the polyester fabric with a Spectra® or Kevlar® fabric. Similarly, the aluminum/honeycomb composite panels in rigid wall shelters (*e.g.*, the MERWS, GP shelter, or ACH) can be replaced with ballistically hardened panels employing Spectra®, Kevlar®, or S2-glass composite skins. An advantage of integral hardness is that the armor material performs other f· nctions, such as providing structural support and environmental shelter, besides providing ballistic protection. A major disadvantage is that ballistic hardening for the weapon threats of interest requires large areal densities of material and the structural frame must be designed to support these heavier loads. The heavier and potentially more numerous shelter components will decrease shelter mobility and increase shelter erection times and costs for all shelter deployments, independent of the deployment threat.

Figure 43 illustrates several approaches to developing ballistically hardened panels. Figure 43.a shows the standard rigid wall shelter panel constructed of aluminum skins with a phenolic impregnated kraft honeycomb core. The simplest hardening upgrade replaces the aluminum skins with ballistic composite skins such as Spectra®, Kevlar®, or S2-glass, as illustrated in Figure 43.b. Spall liners and ceramic appliqué shields can be incorporated as an integral part of the panel or as field installable upgrades [Bless, *et al.*, 1989]. Another approach is to increase the ballistic resistance of core materials (*e.g.*, denser materials, embedded ballistic meshes or fabrics). The final concept incorporates diagonal stiffeners as a means of inducing oblique impacts. Any fragment impacting this panel will encounter at least one oblique surface.

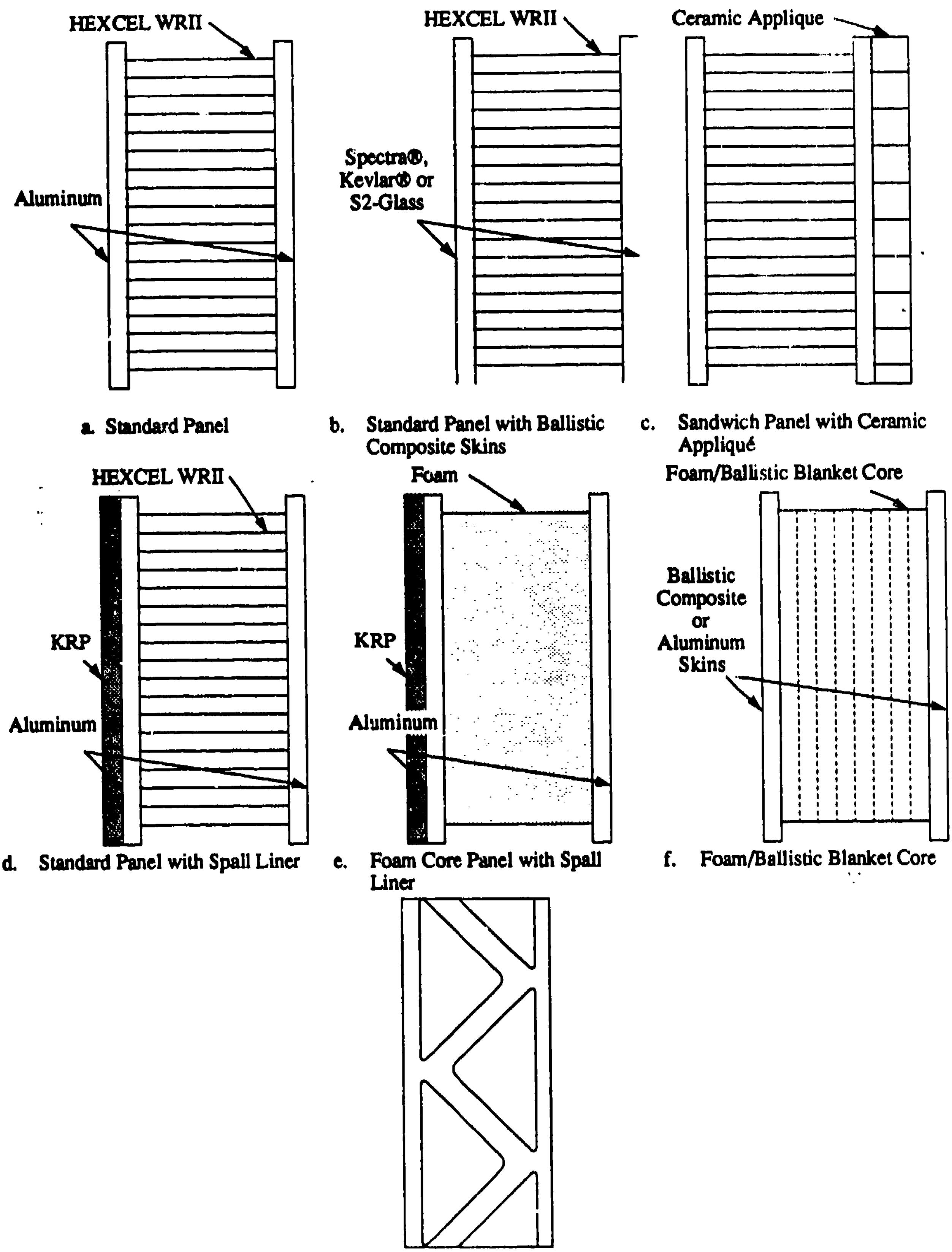
2. Field Installable Hardening Upgrades

In this case armor material is added to the shelter in the field as an upgrade kit. These materials can be added as internal liners or externally as shields. As Figure 44 illustrates, examples of internally mounted armor include fabric liners made of ballistic fibers, composite spall liners on panels, or infill panels between frame members. External shields (Figure 45) include sacrificial panels of monolithic composite materials [Bless, *et al.*, 1989], composite-backed metallic or ceramic armor panels [Askins, 1985], and ballistic blankets. Composite materials are generally more efficient when mounted as internal spall liners [Bless, *et al.*, 1986] or externally with an air gap. Providing a free rear surface permits the composite material to absorb energy through deformation and delamination over a larger area. Shields may be attached to the shelter or free standing, and may be sloped to induce oblique impacts. For shelter-supported hardening upgrades, the basic shelter must be designed to support these loads; hence, a weight penalty will be incurred. For free-standing upgrades, a separate support system must be provided, resulting in larger weight and packing ratio penalties.

3. Field Expedient Hardening Upgrades

Numerous field expedient methods of upgrading shelter hardness have been developed and tested over the last 20 *years*. These methods are described in the Expedient Hardening Addendum to the *PCDM* [Sues, Murphy, and Frank, 1991], and in Army Manual FM 5-103. They are very effective in upgrading shelter hardness and provide a good basis for evaluating the effectiveness of the shelter hardening upgrades. Two of the shelter concepts, the bin-wall shelter and the reinforced earth shelter, incorporate expedient hardening methods into the basic shelter design.

Field expedient hardening methods include: (1) soil berms, (2) sand bagging, (3) sand grids, (4) concrete modular revetments, (5) bin revetments, and (6) sacrificial panels [Sues, Murphy, and Frank, 1991]. The most effective field expedient upgrades rely on placing a soil mass between the shelter and fragmenting munition. The primary design parameter for these upgrades is the thickness of the soil layer used to retard or stop the fragments. Table 18 summarizes equipment and labor requirements, and estimated construction times and costs for typical field expedient upgrades for a small shelter. Figures 46 through 49 illustrate several of these methods as applied to small and large shelters.



a. Standard Panel

b. Standard Panel with Ballistic Composite Skins

c. Sandwich Panel with Ceramic Appliqué

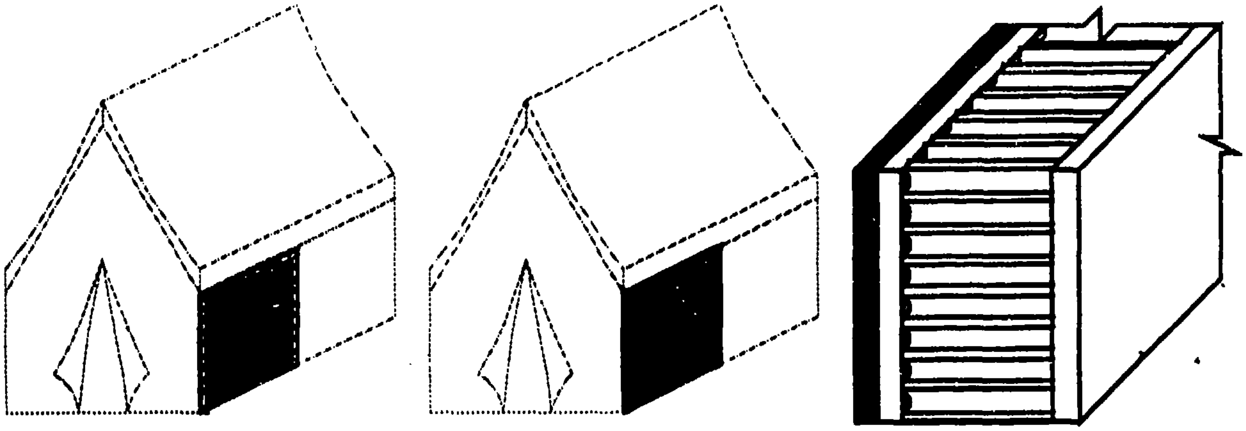
d. Standard Panel with Spall Liner

e. Foam Core Panel with Spall Liner

f. Foam/Ballistic Blanket Core

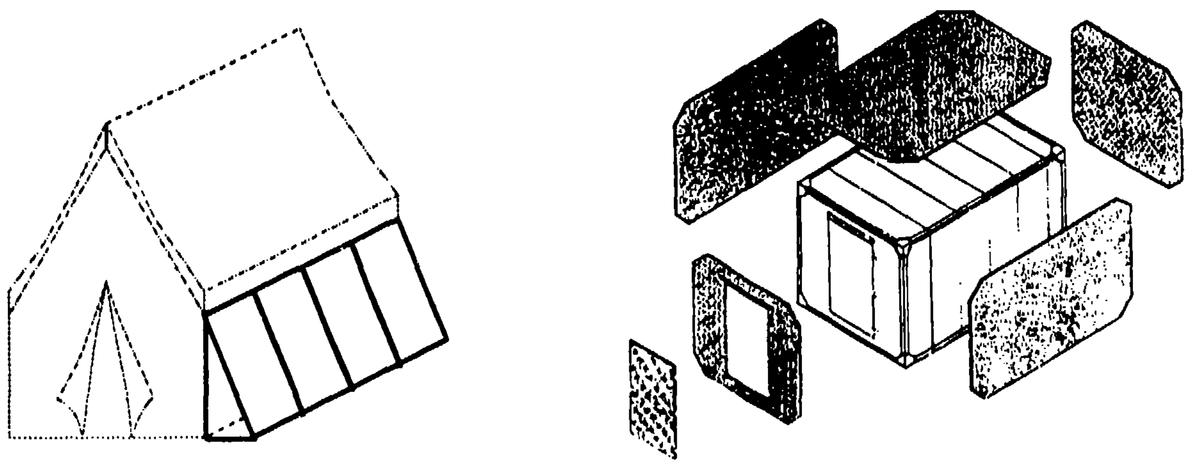
g. Stiffened Panel with Oblique Stiffeners

Figure 43. Ballistic Hardened Panel Concepts.



a. Ballistic Blanket b. Infill Ballistic Panel c. Spall Liners

Figure 44. Internally Mounted, Field-Installable Hardening Upgrades.



a. Exterior Ballistic Panels b. SI/MIKI Tactical Shelter Armor Kit

Figure 45. Externally Mounted, Field-Installable Hardening Upgrades.

D. AIRBLAST ANALYSIS

In this section, we present some preliminary analyses on the airblast response of lightweight portable shelters. After describing the free field and reflected airblast loads considered in the airblast studies, we focus on two basic response modes for rigid panel shelters: (1) localized, single panel bending response and (2) rigid body overturning response. The bending response of a single shelter panel is conservatively approximated as a one-way, simply-supported beam. The equivalent nonlinear SDOF response method given in the Air Force *PCDM* [Drake, *et al.*, 1989] is used to model the panel response. For the rigid body overturning studies, we use design curves developed by Baker, *et al.* [1983] to estimate the shelter response. The overturning studies are limited to small span shelters only, since the aspect ratios (*i.e.*, width to height ratios) of the portable hangar concepts are too large for rigid body overturning to occur.

TABLE 18. FIELD EXPEDIENT HARDENING UPGRADES — SMALL SHELTER ESTIMATES.

Method	Thickness	MH	Equipment Hours	Skill	Airlift	Local Materials	Cost
Berm (Free-Standing)	≥ 3 *feet*	22	8	Heavy Equip.	0 pallets	Soil	\$4.0K
Bermed Wall	≥ 3 *feet*	13	8	Heavy Equip.	0 pallets	Soil	\$2.7K
Sandbag	2.67 *feet*	750	0	Warskill	0.1 pallets	Soil	\$2.7K
Sandgrid	3.17 *feet*	133	8	Heavy Equip.	0.2 pallets	Soil	\$5.4K
Plywood Bin	1 *foot*	144	8	Heavy Equip.	0/4.5[a] pallets	Soil	\$3.5K
Metal Bin	3 *feet*	48	8	Heavy Equip.	1.0 pallets	Soil	\$9.0K

[a]Zero pallets if plywood and dimensional lumber are locally available, 4.5 pallets if materials are air-transported.

Preliminary studies on the sideways response of lightweight plane frame structures were also performed under this task. The response calculations were performed using In-Structure Shock (ISS), a fast-running, nonlinear frame, dynamic response code [Slawson, *et al.*, 1990]. These calculations assumed perfect moment connections between frame members. This highly idealized structural model was not appropriate for airmobile shelters that contain discrete panel and frame connectors (*e.g.*, MERWS). Connections often are the weak link in structural frames and are the areas where failures are initiated. Analysis of the connection behavior requires more detailed modeling (*e.g.*, 3-D finite element). Given the variety of design concepts under consideration, and the preliminary nature of the design concepts, we concluded that detailed structural response studies were beyond the scope of work and could be more efficiently conducted in the next phase of the airmobile shelter research program. Therefore, our initial work on the sidesway response of lightweight shelters is not included in this report.

1. Free Field and Reflected Airblast Loads

As a bounding case, we have selected the 1000-*pound* bomb as the portable shelter airblast threat weapon. Of the six weapon threats considered in the fragment-hardening trade studies, the 1000-*pound* bomb contains the largest quantity of high explosive and is therefore the greatest airblast threat. The Mk83 bomb used to model this weapon has an explosive weight of 420 *pounds*, neglecting casing and equivalent TNT corrections. The incident and reflected pressures and impulses produced by 420 *pounds* of TNT at standoffs varying from 10 *feet* to 400 *feet* are shown in Figure 50. Over these standoffs, incident and normally reflected pressures range from about 650 to 0.8 *pounds/inch*^{2} (*psi*) and from 5100 to 1.7 *psi*, respectively. The incident and reflected impulses range from approximately 200 to 12 *psi-milliseconds* (*psi-ms*) and from 1800 to 22 *psi-ms*, respectively. Although not shown in Figure 50 another important airblast parameter is positive phase duration which varies from approximately 1.7 to 35 *milliseconds* over the ranges of standoffs considered.

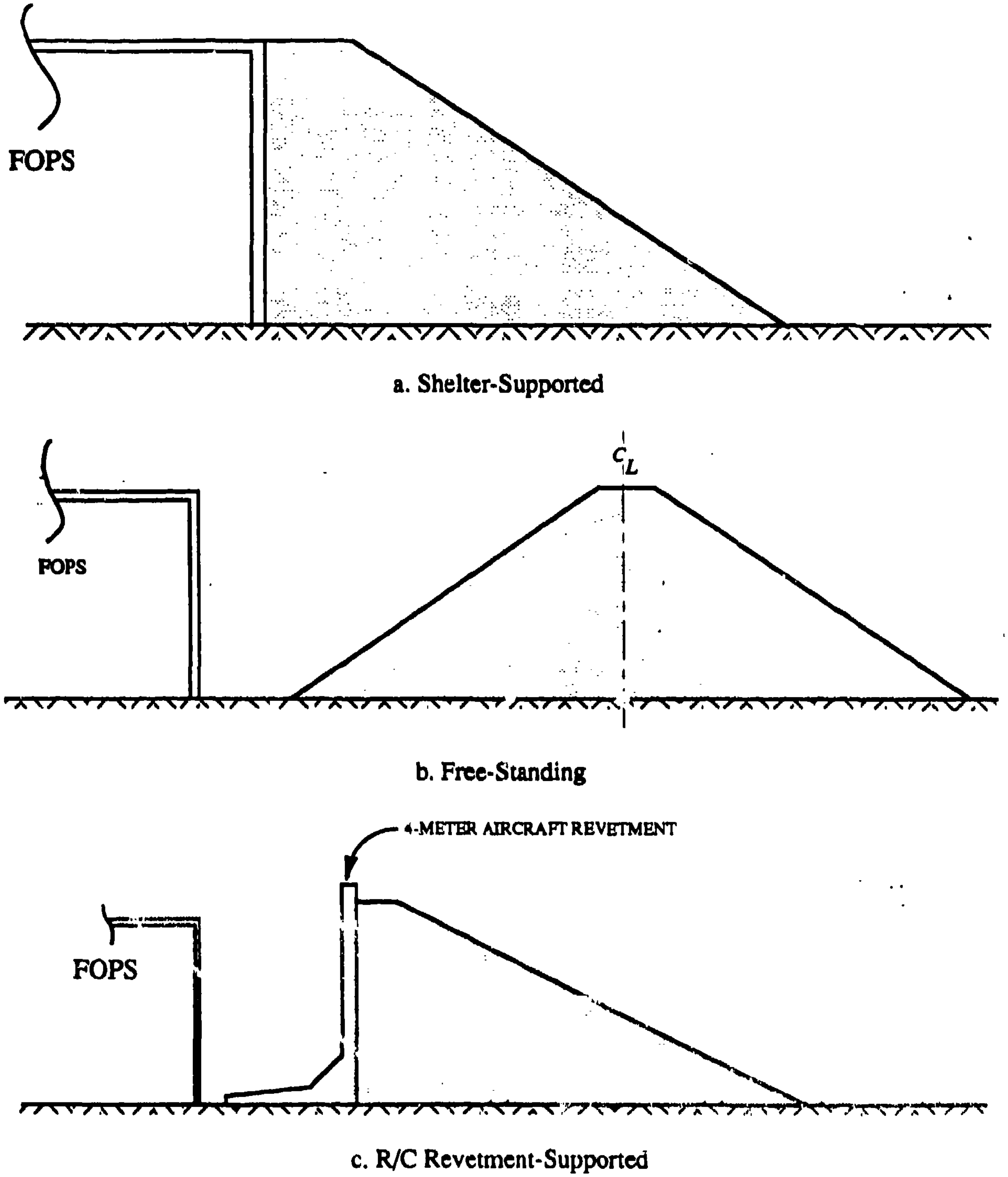
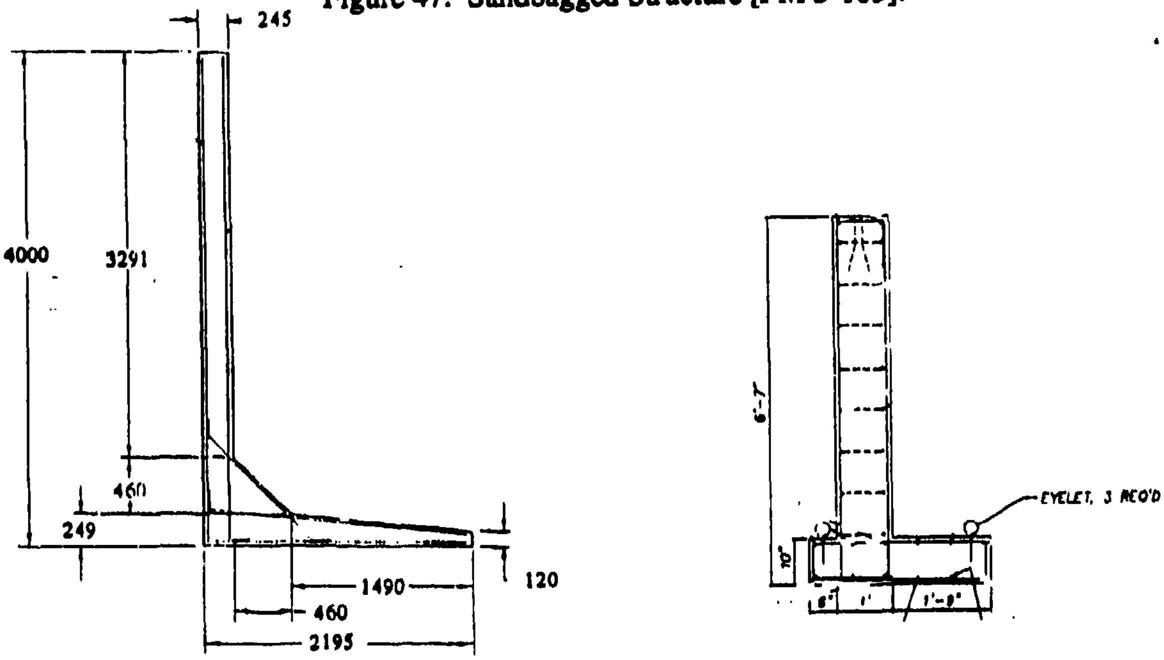


Figure 46. Shelter with Soil Berm [adapted from Drake, *et al.*, 1989].

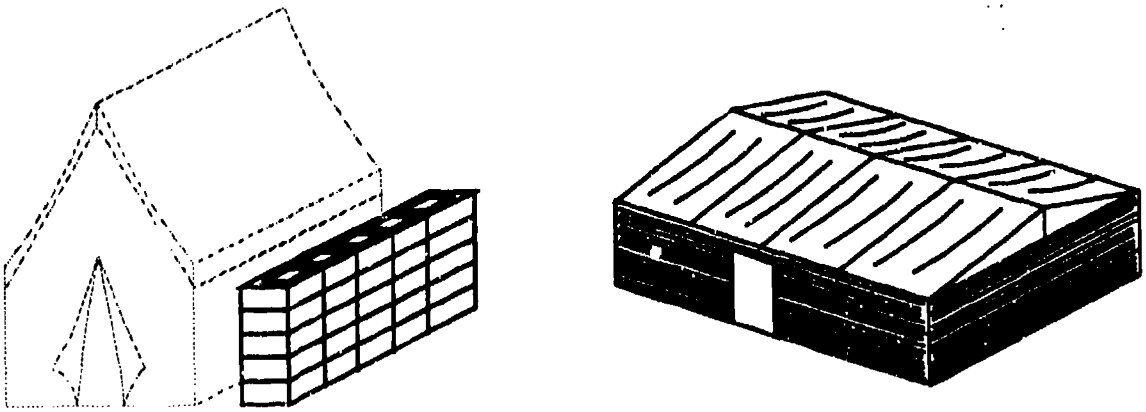
Figure 47. Sandbagged Structure [FM 5-103].



a. 4-*meter* A/C Revetment

b. Bitberg Revetment

Figure 48. Concrete Revetments.



a. Fabric Shelter Upgrade

b. Bin Wall Structure

Figure 49. Bin Revetments.

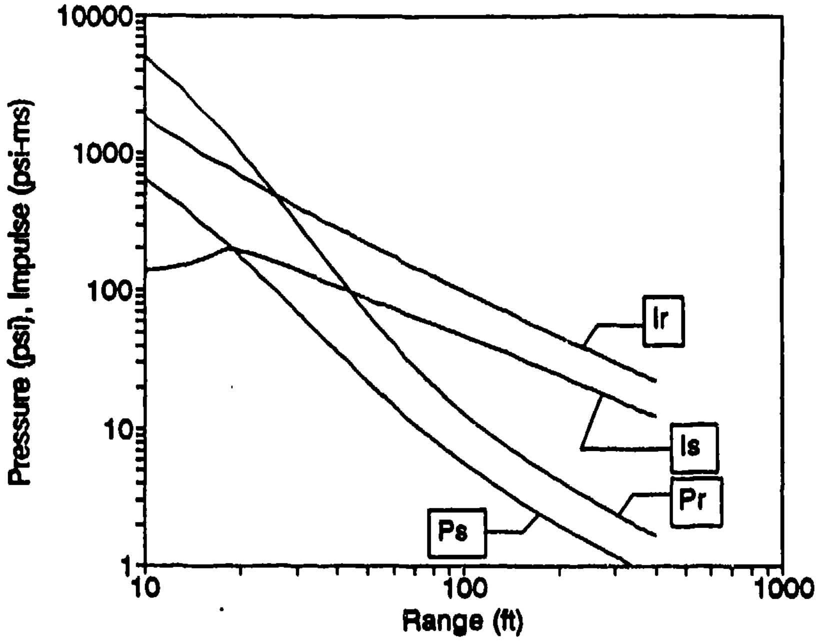


Figure 50. Mk83 Incident and Reflected Pressures and Impulses.

2. Panel Response

The panel response studies are based on the current standard sandwich panel design. This panel consists of one 0.040-*inch* aluminum skin bonded to each face of 2-*inch* thick core material. Transportability constraints effectively limit the size of a typical panel to about 8 *feet* × 8 *feet*. We shall assume that the panel is simply-supported on two opposite edges (as in the Harvest Bare GP or ACH shelters, for example). If we further assume that the panel fails in bending and that the yield stress of the aluminum is approximately 48,000 *pounds /inch*^{2} (*e.g.*, 2024-T4 aluminum), the one-way bending plastic moment capacity per unit width is

$$\begin{aligned} M_p &= (2\ \mathit{inches})\ (48{,}000\ \mathit{psi})\ (0.040\ \mathit{inches}) \\ &= 3840\ \mathit{inch\text{-}pounds/inch} \end{aligned} \tag{1}$$

Equation (X-34) in the *PCDM* provides an energy-based approximation for the peak response of an impulsively loaded equivalent nonlinear single-degree-of-freedom (SDOF) system. Rearranging this equation to solve for the maximum allowable impulse yields

$$I = \sqrt{2K_{LM}\, m\, R_m\, u_m} \tag{2}$$

In Equation (2), K_{LM} is the equivalent SDOF transformation factor (0.66 for the plastic response of a uniformly loaded, simply-supported beam), m is the total mass per unit width (0.0035 *pound-second*^{2}*/inch*^{2} for an 8-*foot* span length), and I is the total impulse per unit width (*pound-seconds/inch*). The peak allowable displacement, u_m, shall be taken as the displacement corresponding to a 8-*degree* plastic hinge rotation at mid-span (*i.e.*, approximately 3.4 *inches*). The peak resistance per unit width, R_m, for a simply-supported beam is

$$R_m = 8\,M_p/l = 320\,pounds/inch \qquad (3)$$

where M_p is the plastic moment capacity defined in Equation (1) and l is the length of the beam (*i.e.*, 96 *inches*). After substituting these values into Equation (2) and dividing by l to obtain the impulse per unit area, the approximate allowable impulse is 23.4 *psi-ms*. This impulse corresponds to the reflected impulse produced by a Mk83 bomb at a standoff of approximately 380 *feet* (see Figure 50). The side-on overpressure is approximately 0.9 *pounds/inch*^{2} at this standoff.

As a check on the accuracy of the equivalent nonlinear SDOF calculations, we performed an ISS calculation for a comparable 8-*foot* simply-supported one-way panel at a standoff of 100 *feet*. The unit reflected impulse at a 100-*foot* standoff is 98.3 *psi-ms*, and a larger plastic moment capacity (5550 *inch-pounds/inch*) is used in this calculation. The peak deflection obtained using ISS is 10.2 *inches*. Substituting these values into Equation (2) and solving for u_m yields an estimated peak deflection of 41.7 *inches*. Although there is a considerable discrepancy between these two estimates, they are on the same order of magnitude despite the fact that the equivalent SDOF method is highly simplified and idealized. The equivalent SDOF model is known to be conservative for predicting the airblast response of traditional protective structures [Twisdale, *et al.*, 1992].

The *PCDM* calculations and the ISS calculations both indicate that there will be a definite need to strengthen the panels in rigid wall shelters to prevent airblast failures. Assuming that total mass is held constant, Table 19 summarizes the plastic moment capacities required to limit the peak panel displacement to 3.4 *inches* (*i.e.*, a plastic hinge rotation of 8 *degrees*). The values in Table 19 are based on Equation (2). The required plastic moment capacity is directly proportional to the squared unit impulse.

The optimal rigid panel design for protective portable shelters should balance the levels of fragmentation and airblast protection for a specific array of weapon threats. This tradeoff must be accomplished within the areal density and volumetric constraints that are necessary to ensure air transportability and rapid shelter assembly. As a bounding example, we have focused our preliminary airblast investigation on the Mk83 bomb, which produces the most severe airblast environment of the six weapons discussed in Section III.B. These calculations indicate that rigid wall panels will need to be substantially strengthened to resist the airblast loads generated by a Mk83 bomb at standoffs of approximately 300 *feet* or less.

Options for strengthening conventional lightweight panels include the use of internal stiffeners as well as thicker and/or higher strength (*i.e.*, composite) skins. Hardened tactical shelter designs for nuclear overpressures in the 7 to 10 *pounds/inch*^{2} range have been developed and tested by the Army [Zartarian, *et al.*, 1981; Milligan, *et al.*, 1984]. We

TABLE 19. ESTIMATED MOMENT CAPACITIES REQUIRED TO PREVENT FLEXURAL FAILURE OF A STANDARD SANDWICH PANEL.[a]

Standoff (*feet*)	Unit Impulse (*psi-ms*)	Required M_p (*inch-pounds/inch*)
50	217.0	332,000
100	98.3	68,000
200	46.6	15,300
400	22.5	3,600

[a]Mk83 weapon; simply-supported, one-way panel response; 2 *psf* areal density; 8-*foot* span.

recommend that these and other design options be considered in more detail in the next phase of the airmobile shelter research program after the most promising design concepts have been identified and feasible levels of fragmentation protection have been established.

3. Overturning

Tactical shelters have been shown to be vulnerable to overturning when exposed to moderate nuclear blast overpressures [Milligan, *et al.*, 1982]. In this section, we briefly investigate the possibility of rigid body overturning for a generic box-shaped small shelter concept with an 10-*foot* by 20-*foot* rectangular cross-section. As in the previous section, we will use a Mk83 bomb as the threat weapon. The analysis is based on a set of target overturning design curves developed by Baker, *et al.* [1983]. The curves are reproduced in Figures 51 and 52. If the specific impulse imparted to the target (Figure 52 exceeds the specific impulse threshold of the target (Figure 52), then the target should overturn.

The first step is to estimate the impulse threshold of the rigid, small shelter target. The scaled target height is 10 *feet* divided by 20 *feet*, or 0.5. This places the shelter on the bottom edge of Figure 52. Generally, it is most conservative to assume that the shelter is empty. This would place the height of the center of gravity at about one half of the shelter height (*i.e.*, $h_{cg}/h = 0.5$). Thus, the normalized specific impulse threshold can be taken conservatively as 0.5. Solving for i_θ yields

$$i_\theta = 0.50 \frac{W b^{3/2}}{A h_{bl} g^{1/2}}$$

$$= 49.3 \; psf\text{–sec} \qquad (4)$$

$$= 342 \; psi\text{–}ms$$

where we have used the following values: height to center of pressure, $h_{bl} = 5.0$ *feet*; weight per unit depth, $W = 120$ *pounds/foot* (*i.e.*, areal density equals 2 *pounds/foot*^{2}); presented area per unit depth, $A = 10$ *feet*^{2}*/foot*; width, $b = 20$ *feet*; and gravity, $g = 32.2$ *feet/second*^{2}.

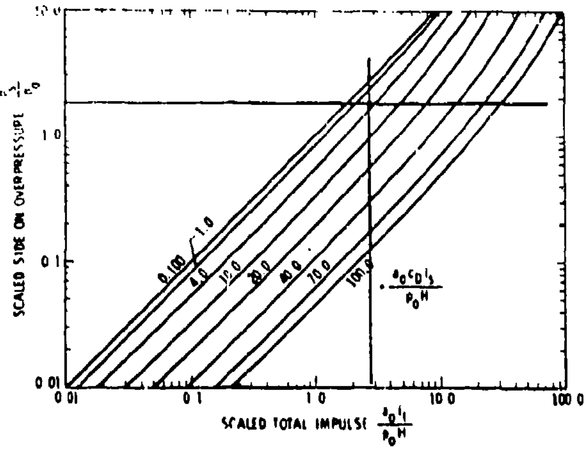


Figure 51. Specific Impulse Imparted to a Target that Might Overturn [Baker, *et al.*, 1983].

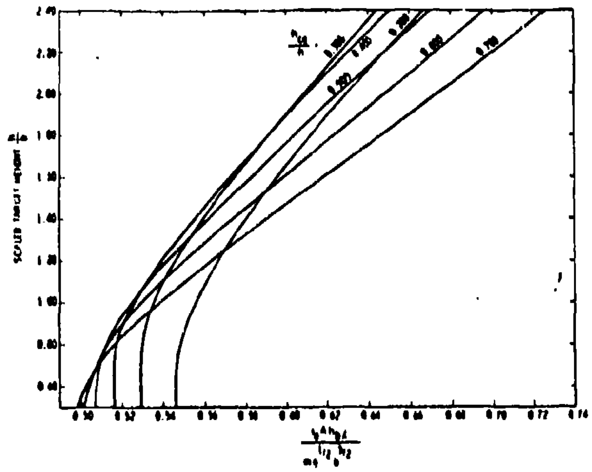


Figure 52. Impulse for Threshold of Overturning [Baker, *et al.*, 1983].

Next, Figure 51 is used to determine the weapon standoff by setting the imparted impulse equal to the overturning impulse. Thus, we enter Figure 51 at a scaled total impulse of 2.5. The scaled total impulse is computed using the following values: ambient sound velocity (a_0 = 1079 *ft/sec*), imparted impulse (i_t = 49.3 *psf-sec*), ambient atmospheric pressure (p_0 = 2117 *psf*), and the smallest target dimension (H = 10 *feet*). The remaining parameters in Figure 51 are the drag coefficient, C_D, which is taken as 1.8 for rectangular shapes; the free field side-on overpressure, P_s; and the free field side-on impulse, i_s. The latter two parameters are coupled for a given yield and standoff. After several trial and error iterations, we find that overturning is predicted for standoffs of approximately 45 *feet* or less for a Mk83 bomb. At this range, p_s/p_0 is 1.88 and $a_0 C_D i_s / p_0 H$ is 1.26. As desired, these values intersect in Figure 51 at a scaled total impulse of 2.5.

Our conservative analysis of small shelter overturning indicates that the standoffs required are well within the standoffs at which severe localized panel damage is likely (see Section III.D.2). Therefore, overturning is very unlikely to be a controlling failure mode for typical small span shelter geometries unless the panels are capable of resisting reflected impulses in excess of 200 *psi-ms* (see Table 19). We come to this conclusion even though we have conservatively estimated several key overturning parameters (a high center of gravity; an empty, lightweight shelter; and a high drag coefficient) and even though the model implicitly assumes that all of the impulse energy goes into rigid body motion (*i.e.*, no shelter deformation).

E. SMALL ARMS HARDENING ASSESSMENT

In this section, we provide a preliminary assessment of hardening shelter walls to stop small arms fire. This assessment assumes normal collinear impacts at the projectile muzzle velocity and is restricted to common projectiles for small arms fire (5.56 and 7.62-*mm* ball ammunition and 9-*mm* FMJ projectiles) and monolithic composite panels. The data for the assessment are extracted from the Air Force *PCDM*, the *Lightweight Armor Design Handbook* [MTL, 1990] and data provided by Allied-Signal [Allied Signal, Inc., 1992]. The Kevlar® data used in the assessment are for K29 with standard processing. The performance of KM2 is expected to be much better than that for K29. We stress that the ballistic protection provided by these materials are resin, weave, and fiber-denier dependent and must be independently verified during prototype design and development.

Figure 53 compares the ballistic protection provided by Spectra Shield™ (Kraton Thermoplastic resin), S2-glass (Phenolic resin), and Kevlar® (Phenolic/PVB resin) monolithic composite panels against 7.62-*mm* projectiles. Muzzle velocities (Table 15) range from 1000 to 2900 *fps*. Stopping all threats requires approximately 4.5 *psf* of Spectra Shield™ material. The stopping power of S2-glass and K29/Standard is much less and would require approximately 9.0 *psf* of S2-glass and 14 *psf* of Kevlar®, based on a linear extrapolation of the data, as shown in Figure 53. Ballistic limit velocities are higher for the 5.56-*mm* M193 round, but fall significantly for 7.62 × 39-*mm* (AK-47) and 9-*mm* FMJ projectiles, as shown in Figures 54 through 56. Figure 56 shows that stopping a 9-*mm* FMJ at a muzzle velocity of 1450 *fps* requires 0.5 *psf* of Spectra Shield™ compared to 1.5 *psf* of Kevlar®.

In summary, we conclude that 3 to 5 *psf* of composite materials will provide substantial small arms protection. As shown in Figures 53 through 56 these areal densities will stop most 7.62 and 9.0-*mm* projectiles. Spectra Shield™ generally provides the best protection; however, based on FSP ballistic data, we expect that KM2 with special processing will provide comparable protection. S2-glass performance will lag that for Spectra® and KM2 in terms of areal weight density; however S2-glass will be competitive in terms of cost and packing volume.

F. FRAGMENT HARDENING — MODEL DEVELOPMENT

In this section, we describe the fragment spray and perforation model used to assess the integral and upgraded hardening options against the selected munitions. Existing fragment analysis procedures, such as those presented in the Air Force *PCDM* are not reliable in that: (1) the procedures consider only the fragment weight distribution in specifying the design fragment

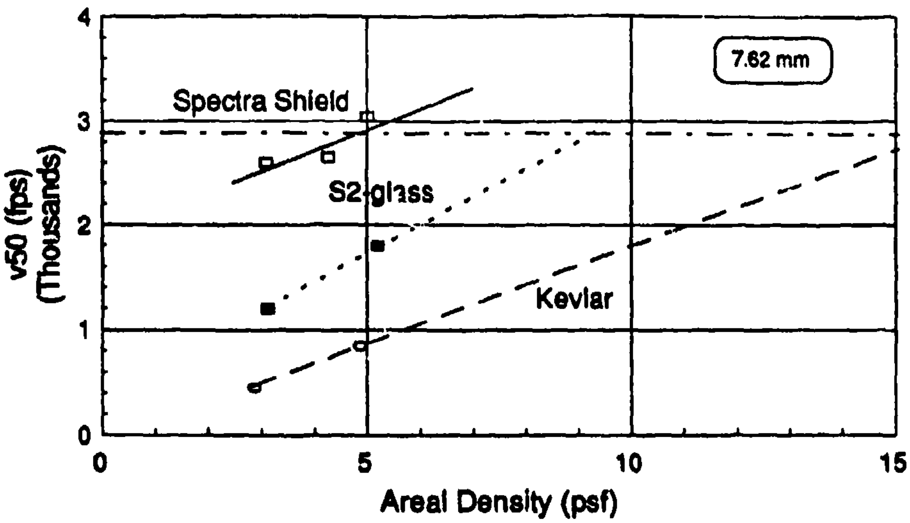


Figure 53. Monolithic Composite Panel Ballistic Limit Velocities — 7.62-*mm* Projectiles [after Allied Signal, 1992].

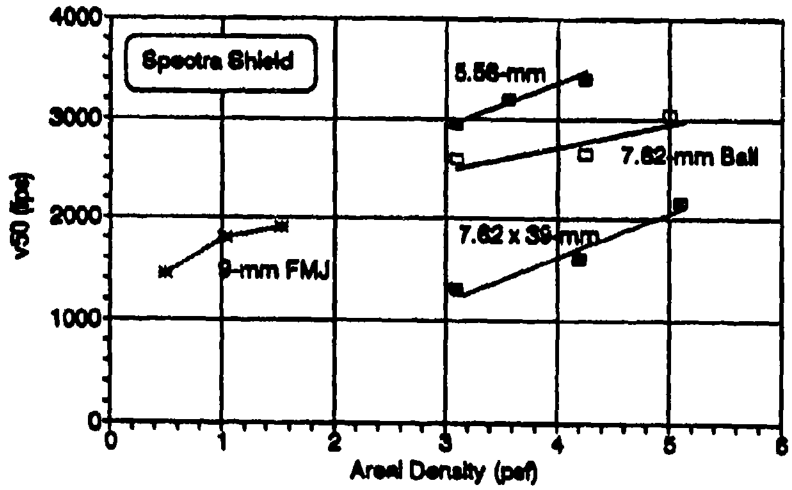


Figure 54. Monolithic Composite Panel Ballistic Limit Velocities — Spectra Shield™.

and do not account for the number of fragments generated or the probability that the design fragment will strike the target [Twisdale, *et al.*, 1992]; (2) do not accurately model the fragment spray pattern; (3) assume a worst case fragment impact (normal, collinear impact); and (4) are overly conservative in that they generate larger average fragment weights and higher initial velocities than observed in arena testing. For example, the AF *PCDM* recommends modeling the munition as a uniformly expanding sphere or cylinder. As demonstrated in Figure 57, the assumption of a cylindrical line-source or a spherical point-source has an order of magnitude effect on the number of predicted impacts.[1] Both models predict that 50 *percent* of the fragments generated will impact the structure for the limiting case of a contact burst. As the

[1] Both models assume uniform spray patterns.

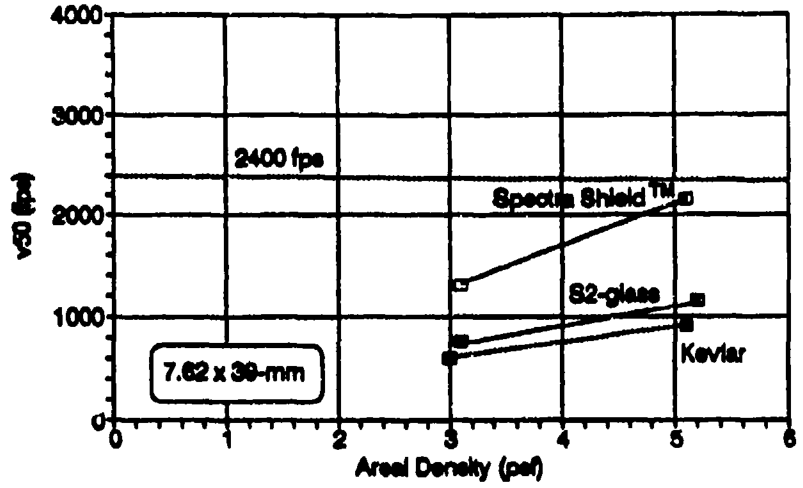


Figure 55. Monolithic Composite Panel Ballistic Limit Velocities — 7.62-*mm* × 39-*mm* Projectiles.

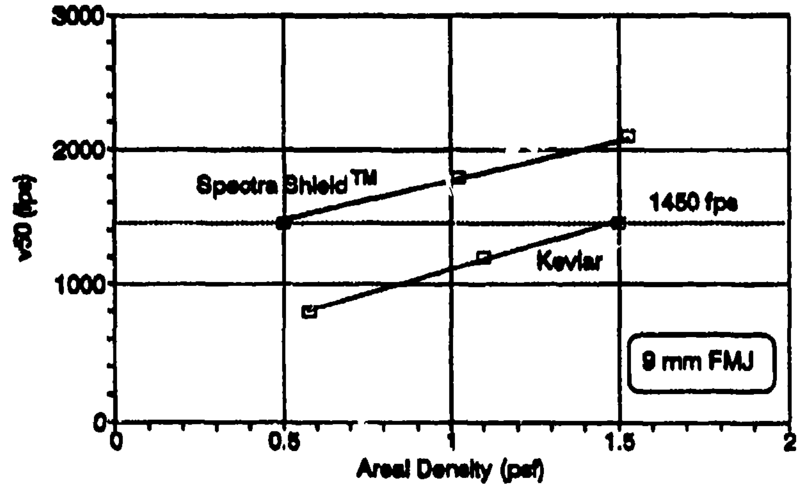
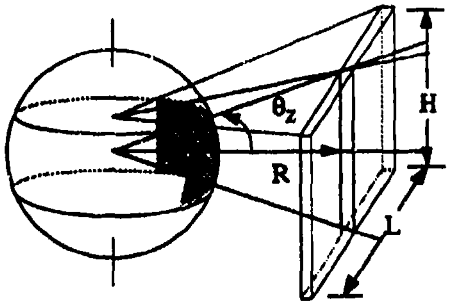


Figure 56. Monolithic Composite Panel Ballistic Limit Velocities — 9-*mm* FMJ Projectiles.

weapon standoff increases, the fraction of impacts for the spherical point source drops off rapidly. At a standoff of 100 *feet*, the cylindrical line source predicts 50 times more fragment impacts than predicted by the spherical point source. This magnitude of error can have a significant impact on the hardening feasibility for FOPS. Consequently a more accurate weapon fragment analysis model was developed for the fragment hardening assessment.

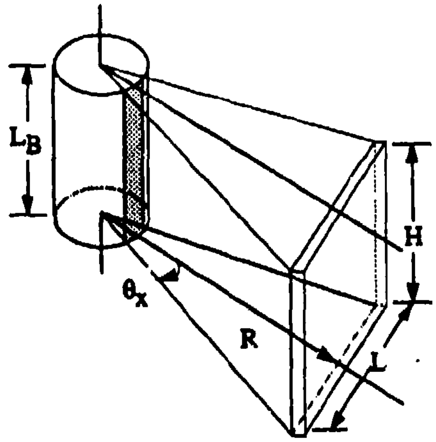
1. SAFE Model Overview

The fragment analysis model, illustrated in Figures 58 and 59, is implemented in the Survivability Assessment for Fragmentation Effects (SAFE) code. Figure 58 presents the



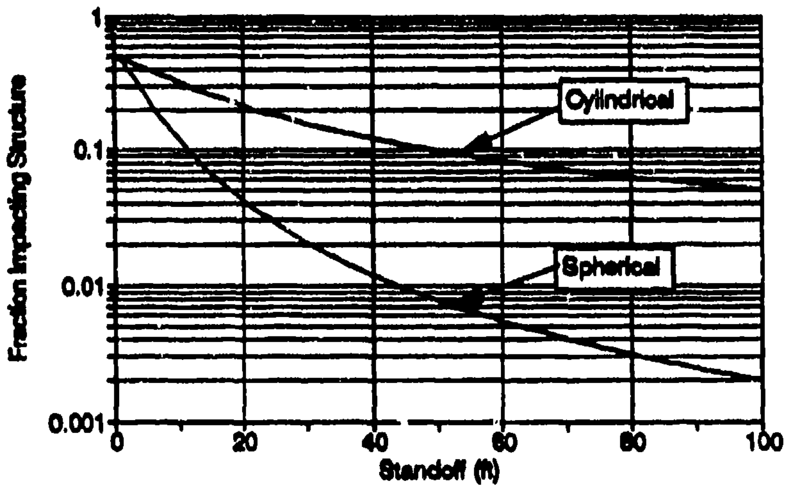
$N_i/N_f \sim (\theta_x/\pi)(h/R)$
$h = R \sin \theta_z$
$\theta_x = \tan^{-1}(H/2R)$

a. Point Source



$N_i/N_f = (\theta_x/\pi)$ $L_B \leq H$
$N_i/N_f = (\theta_x/\pi)(H/L_B)$ $H < L_B$

b. Cylindrical Source



c. Fraction of Fragments Impacting Wall

Figure 57. Spherical and Cylindrical Fragment Source Models.

solution methodology for SAFE. The methodology consists of models for the weapon fragmentation characteristics, fragment transport, and target perforation resistance. The fragmenting munition is represented by a grid of cells mapped on the munitions surface and is permitted to have arbitrary impact coordinates, orientation, and velocity as illustrated in Figure 59. The position, length (L_B), and orientation of the munition at detonation are specified by the x, y, z coordinates of the nose and tai . The munition-fragmentation characteristics are assumed to be axisymmetric and are given by the fragment mass distribution, ejection velocity, and

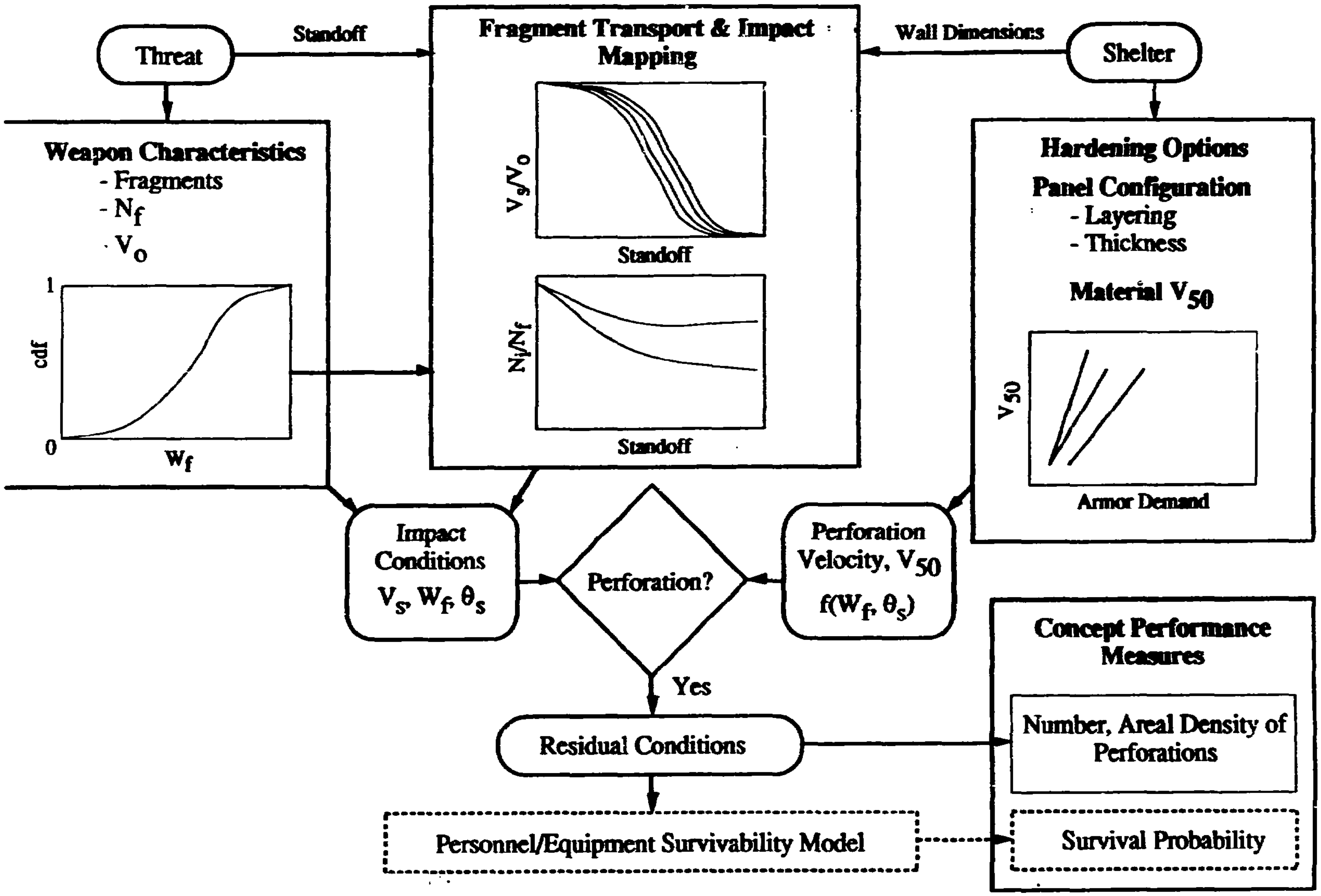


Figure 58. SAFE (Survivability Analysis for Fragment Effects).

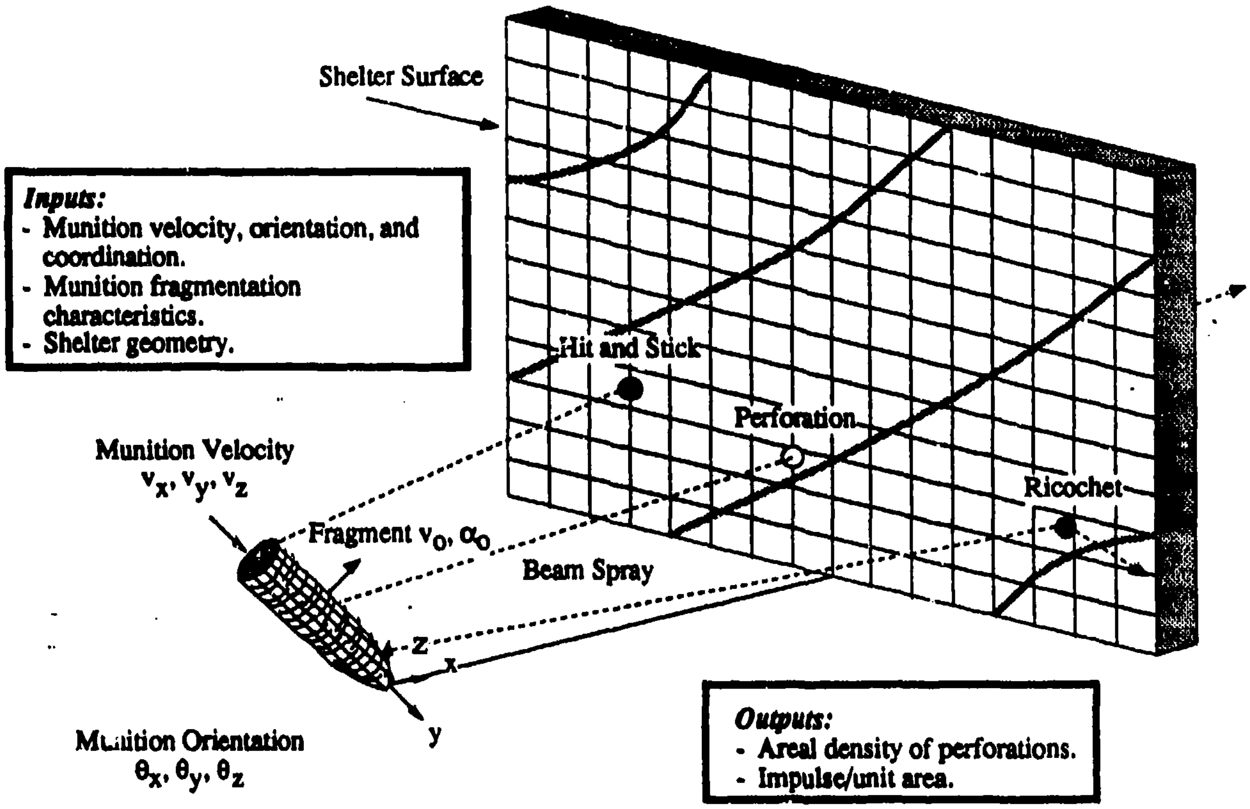


Figure 59. SAFE Weapon and Target Models.

ejection angle. These properties are, however, permitted to vary along the length of the weapon, as is the mass distribution of the munition. The target is assumed to be made up of a collection of planar surfaces, which can be arbitrarily oriented in space with each surface being defined by up to ten vertices. The fragment spray pattern is mapped onto the target surface by projecting the centroid of individual bomb cells onto the target using straight line trajectories.

SAFE calculates the critical fragment weight, and the number and areal density of perforations semi-empirical perforation models, such as the THOR equations [Drake, *et al.*, 1989]. The critical fragment weight, W_{50}, is the weight of the smallest fragment that will have a 50 *percent* probability of perforating the armor as determined using empirical ballistic limit curves (*i.e.*, v_{50} curves). The number of perforations caused by a given weapon cell is computed by multiplying the expected number of fragments produced by the weapon cell by the fraction of fragments having weights greater than the weight of the critical fragment. Neither of these terms is integer valued; therefore, the number of perforations caused by each bomb cell is not a whole number. Although not currently implemented, the model is designed to facilitate future enhancements, such as inclusion of a personnel/equipment survivability model for calculating survival probabilities.

There are two major components to the input data required by the SAFE model: the fragment environment data and the target data. Fragment environment input data required includes: (1) weapon type (*i.e.*, explosive weight, casing weight, geometry, etc.); (2) weapon coordinates and velocity at detonation; (3) bomb cell grid (determines resolution); (4) weapon fragmentation characteristics (ejection angle, initial velocity, and weight distribution as a function of position along bomb axis; and (5) casing weight distribution along the bomb axis. Target input data required includes: (1) number of planar surfaces; (2) number and coordinates of vertices on each planar surface; (3) material composition of the wall (material types, thicknesses, densities, and number of layers); and (4) material perforation resistance (V_{50} and V_r curves).

2. Weapon Fragmentation Model

The munition-fragmenting characteristics are assumed to be symmetric about the axis of the weapon and are described by the cumulative mass distribution, Mott's constant, ejection angle, and initial fragment velocity at discrete locations along the weapon axis. These data can derived from analytical models of the munition detonation or empirically derived from arena test data. We have used the latter approach to derive fragmentation models for the six munitions selected for the hardening trade studies.

The approach used in deriving these models is illustrated in Figures 60 through 65 for a Mk83 1000-*pound* bomb.[1] Fragment data (number and weight) from arena tests [JTCG, 1992] are mapped onto the longitudinal axis of the weapon by calculating the cumulative fragment weight as a function of polar angle and comparing this distribution to the cumulative mass distribution along the bomb axis. Assuming no overlap in the fragment spray pattern between adjacent points along the bomb axis, the normalized CDFs for the bomb weight and arena fragment weight provide a one-to-one relationship between the polar angle and distance along the bomb axis. This relationship provides the basis for mapping the fragment weight distribution, ejection angle, and initial fragment velocity onto the bomb axis.

Figure 60 presents the cumulative fragment mass by polar angle for nose and tail initiated Mk83 bombs filled with H-6 and PBX-109 explosives [*JMEM*]. These curves indicate that approximately 60 *percent* of the casing weight is ejected as fragments in the beam spray of the Mk83. Fragments from the beam spray impact the collection bundles over a 20 to 25-*degree* spray with the spray being skewed depending on whether the bomb is nose (80 to 105 *degrees*) or tail-initiated (60 to 85 *degrees*).

Figure 61 compares the normalized cumulative fragment and bomb weight distributions for the Mk83 bomb. The bomb mass was estimated using the bomb schematic shown in Figure 61 assuming a constant wall thickness. Comparison of this distribution with the fragment weight distribution indicates that the fragment data can be adequately mapped using six linear segments, with the beam spray region falling between $x = 31.6$ and $x = 86.3$ *inches*, where x is measured from the bomb nose. The segment boundaries are summarized in Table 20.

[1] The *JMEM* recommends that the Mk83 arena test data be used for munitions area effectiveness (MAE) calculations. Therefore, we have selected the nose-initiated Mk83 as the representative weapon for the 1000 *pound* bomb.

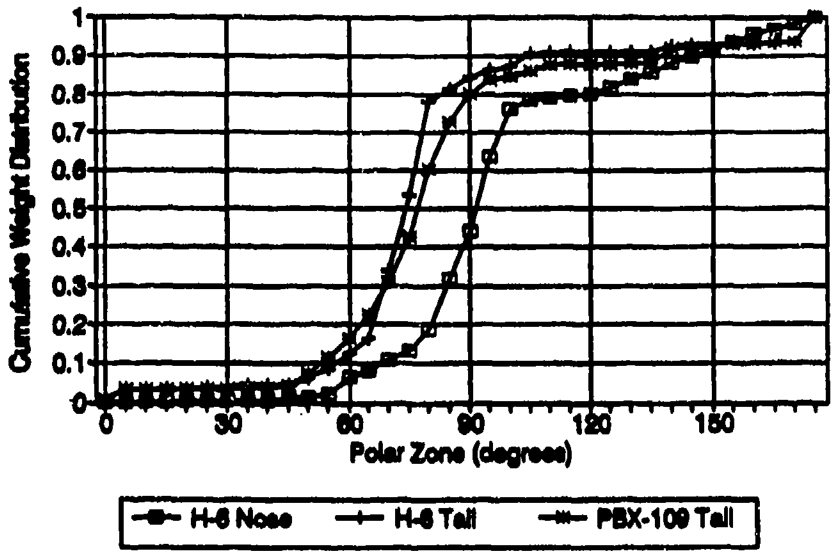


Figure 60. Cumulative Fragment Weight Distribution for Nose and Tail-Initiated Mk83 Bombs.

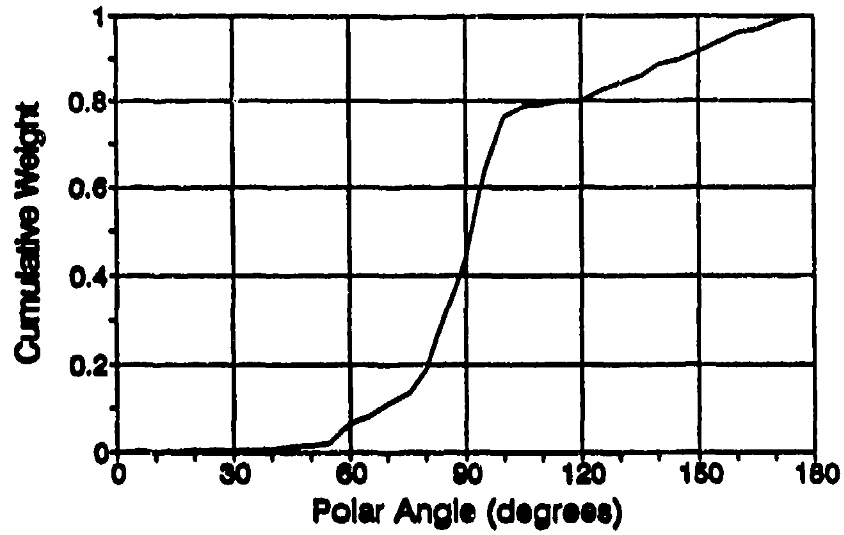
The fragment ejection angle varies along the bomb axis and can be derived from the polar angle in which the fragment was recovered considering the geometry of the arena tests. This process is illustrated in Figure 62. From geometry, the ejection angle α depends on the distance from the bomb centroid (a) and is given by

$$\alpha = \tan^{-1}\left(\frac{\cos\theta - a/R}{\sin\theta}\right) \tag{5}$$

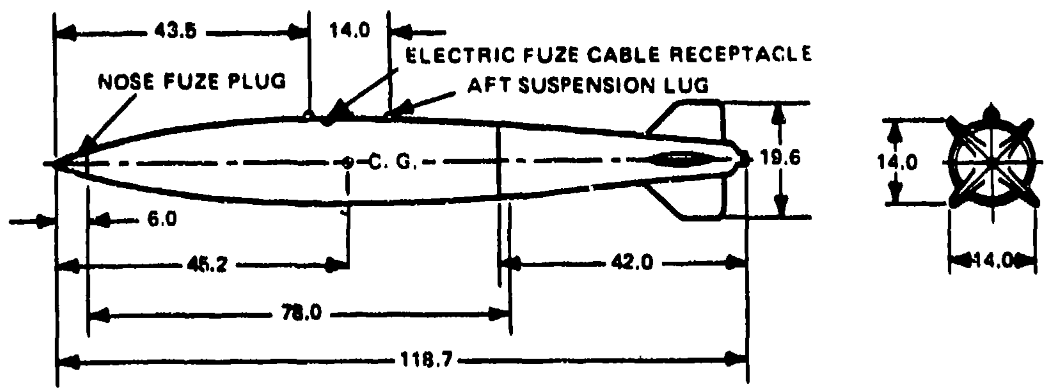
where θ = polar angle where the fragment was recovered. Plots of the ejection angle for various ratios of a/R are shown in Figure 62.b. For most cases, we expect the maximum a/R to be less than 0.05, so that a/R ~0 and

$$\alpha = \tan^{-1}(\cot\theta) = 90 - \theta \tag{6}$$

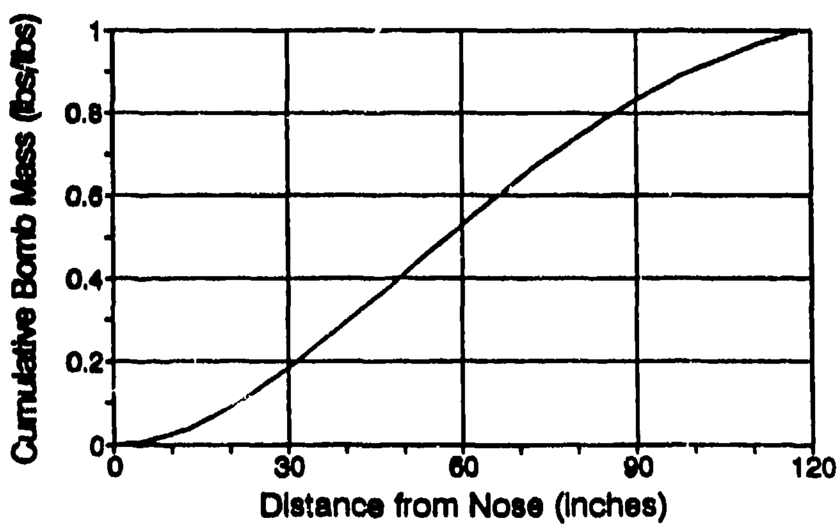
The fragment weight distribution also varies along the bomb axis. Figure 63 compares the fragment weight distribution for the beam spray region with the overall fragment weight distribution for the Mk83 while Figure 64 plots the Mott's parameter for cross-sections along the bomb axis. Mean fragment weights for the beam spray are shown to be slightly larger than the overall bomb distribution, which includes large fragment chunks ejected from the nose of the bomb. As shown in Figure 61, fragments from the nose region between 0 and 57.5 *degrees* comprise fewer than 10 *percent* of the total weight of fragments generated. These large fragments are offset by smaller fragments generated in the tail region of the nose-initiated Mk83. As a result, the Mott's parameter for the bomb as a whole is very close to the Mott's parameter for the beam spray region which contains 60 *percent* of the total number of fragments. Figure 65 plots the fragment ejection velocity as a function of polar angle. The fragment ejection



a. Fragment Distribution

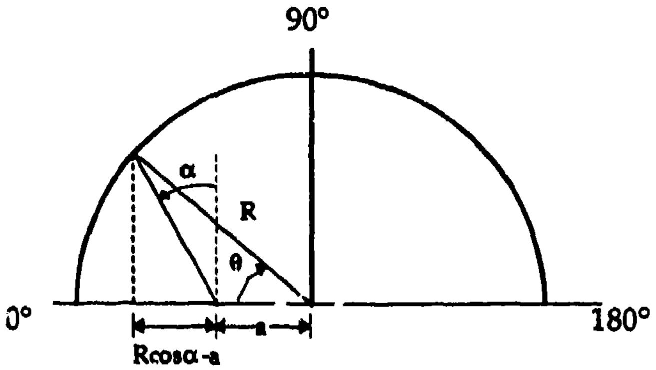


b. Bomb Schematic

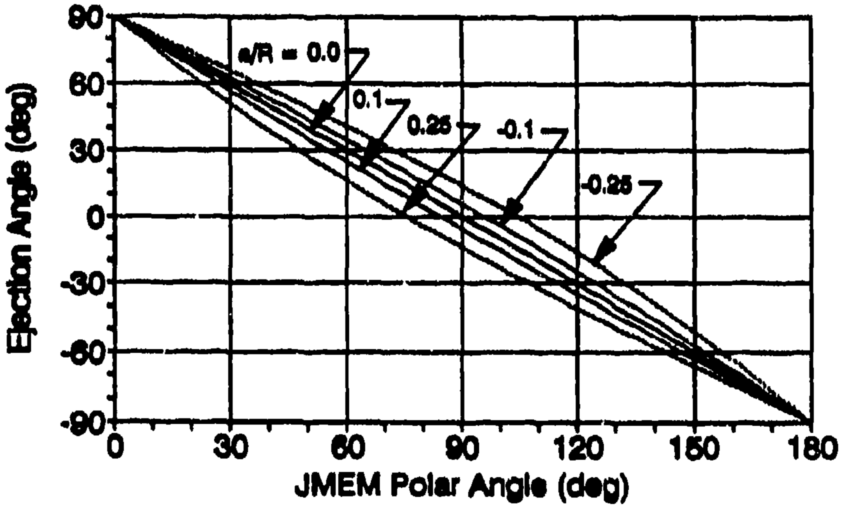


c. Bomb Weight Distribution

Figure 61. Fragment and Bomb Weight Distributions for Mk83 Bomb.



a. Arena Test Set-Up



b. SAFE Ejection Angles

Figure 62. Fragment Ejection Angle Mapping Using Arena Test Data.

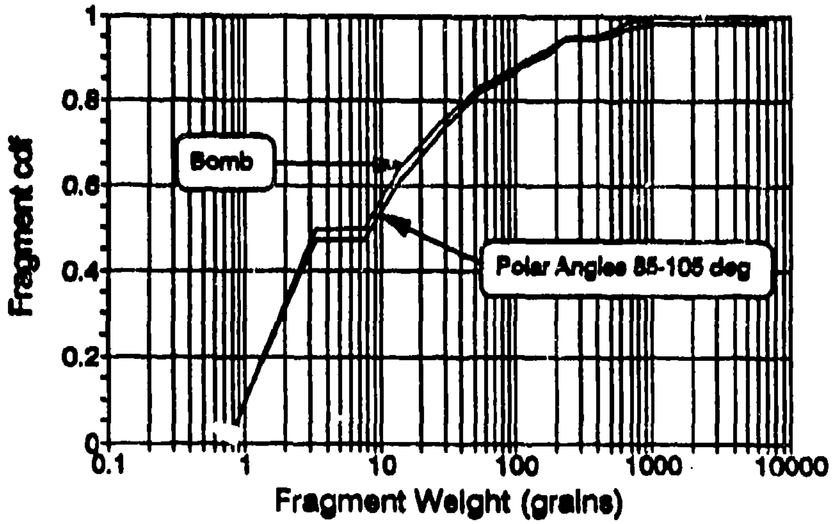


Figure 63. Beam Spray and Overall Fragment Weight Distributions for Mk83 Nose-Initiated Bomb.

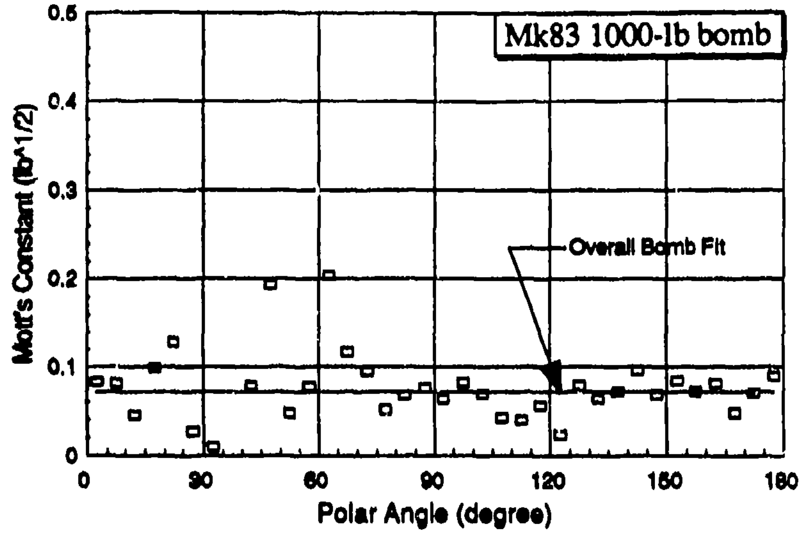


Figure 64. Variation in Mott's Constant by Polar Angle.

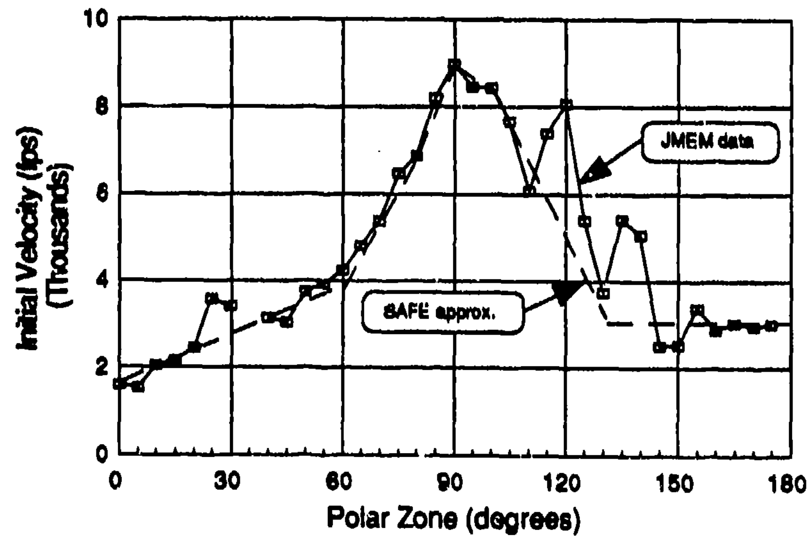


Figure 65. Fragment Ejection Velocities for Mk83 Bombs.

velocity varies from a low of 1600 *feet/second* in the nose to 9000 *feet/second* in the beam spray region. The piecewise linear fit to the fragment ejection velocity is summarized in Table 20.

Table 20 summarizes the SAFE fragment input data for the Mk83. Following the steps outlined above, SAFE fragment models have been developed for the 40-*mm* aircraft cannon ammunition, a generic cluster munition, 152/155-*mm* artillery round, a 122-*mm* rocket, and a 250-*pound* missile. The input data for these munitions are summarized in Appendix G of Volume II.

TABLE 20. SAFE FRAGMENT MODEL FOR Mk83 NOSE-INITIATED BOMB

Polar Angle (*degrees*)	Weight CDF	Bomb Axis x (*inches*)	Ejection Angle (*degrees*)	Ejection Velocity (*fps*)	Mott's Constant (*pounds*$^{1/2}$)
0	0.000	0.0	87.4	1600	.0830
60	0.022	8.5	30.5	3900	.0830
85	0.188	29.7	6.5	6900	.0873
95	0.440	52.6	0.441	9000	.0725
105	0.763	82.2	-10.2	8400	.0725
125	0.800	86.3	-30.2	3000	.0432
180	1.000	118.7	-87.3	3000	.0748
Overall					.0721

[1]Midpoint of polar zone

3. Fragment Transport and Impact Mapping

The fragment spray pattern is mapped onto the target surface by superimposing a regular grid of latitudes and longitudes onto the weapon surface to create a set of weapon cells. These cells are projected onto the target surface assuming straight line trajectories emanating from the longitudinal axis of the munition. This approximation neglects the effects of gravity, which would lower the impact coordinate by the distance, Δz, given by

$$\Delta z = 1/2\, gt^2 \tag{7}$$

where

g = acceleration due to gravity (32.2 *feet/second*^{2}),

$t = \dfrac{e^{k_v R} - 1}{v_o\, k_v}$ = fragment flight time (based on *PCDM* Equation (VI-22)),

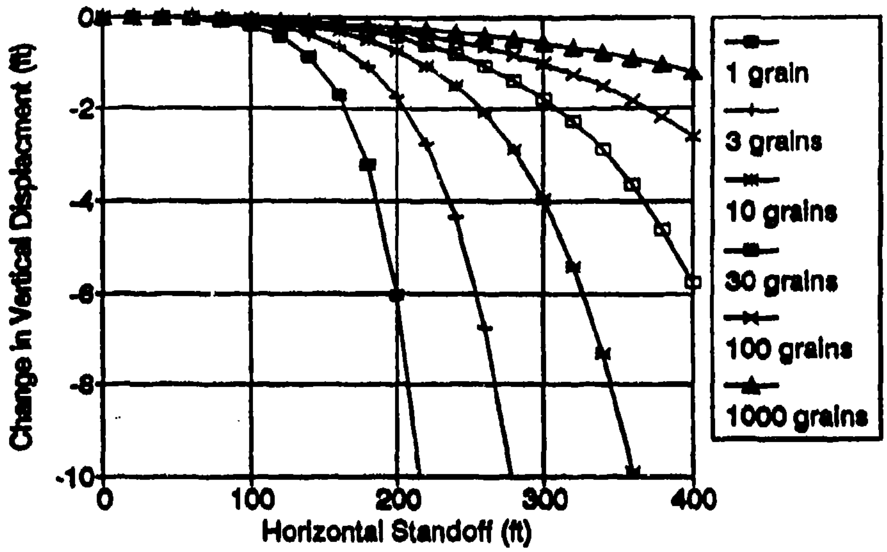
R = horizontal standoff (*feet*),

$k_v = \dfrac{0.00077}{W_f^{1/3}}$ = velocity decay constant (1/*foot*)[1], and

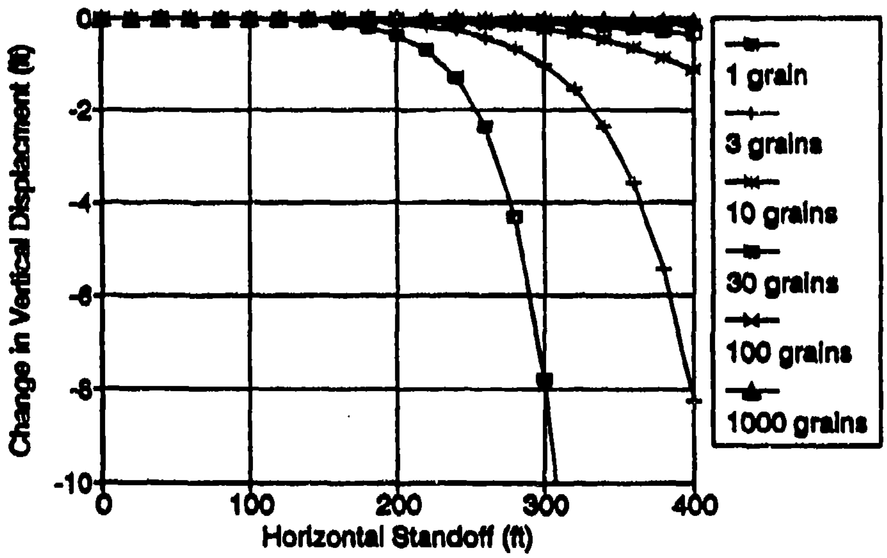
v_o = initial fragment velocity (*feet/second*).

Figure 66 plots the vertical drop for various fragment weights with initial velocities of 2000 and 8000 *fps*. These curves indicate that gravity effects are greatest for small, slow-moving fragments. Small fragments have greater velocity attenuation; consequently, their flight times and Δz's are larger than their more massive counterparts. In terms of perforations,

[1] Assuming the standard fragment shape, CD = 0.6, and specific air weight of 9.977 *pounds/feet*^{3}.



a. $vo = 2000\,fps$



b. $vo = 8000\,fps$

Figure 66. Change in Vertical Displacement due to Gravity Effects.

these smaller, slow-moving fragments are easier to stop, so that the number of perforations is not likely to be influenced substantially for targets with significant levels of protection. Finally, while gravity effects may result in some fragments striking the ground prior to reaching the target, these misses will be offset by hits from fragments that would have flown over the target had gravity effects not been considered. Thus, we conclude that the effect of gravity on the number of perforations is small and can be safely neglected for the velocities and ranges of interest.

Figure 67 presents the SAFE mapping of fragment cell impacts from a 1000-*pound* GP bomb onto a vertical wall. The bomb in this case was oriented vertically with its center of gravity (CG) at the wall midpoint. The fragment impact pattern clearly displays the high density band of impacts in the beam spray region and the spherically divergent impacts off the ends of the bomb. Impact densities are also seen to be highest in the center and decrease towards the edges of the wall.

The fragment striking velocity, v_s, is approximated by the exponential function [Drake, *et al.*, 1989]

$$v_s = v_o \exp(-k_v R) \tag{8}$$

$$v_s = v_o \exp(-7.70 \times 10^{-4} R/W_f^{1/3}) \tag{9}$$

This equation assumes a standard fragment shape which is cylindrical with a hemispherical nose shape (slightly different than the chisel-nose shape used in ballistic testing) and a drag coefficient of 0.6. In reality, the fragment shapes are random; consequently, there may be considerable scatter in the magnitude of the velocity decay. Furthermore, there may be conservative or unconservative biases in the velocity decay equation.

Figure 68 plots the velocity decay as a function of range (weapon standoff) for selected fragment weights. Lightweight fragments attenuate the most rapidly, with the velocity for a 0.01-*grain* fragment decaying to approximately half of its initial velocity in 10 *feet*. Heavier fragments, such as the 1000-*grain* fragment retain 80 to 90 *percent* of their initial velocity after 100 *feet*.

The fragment transport and impact model also provides the fragment impact obliquity. As is shown in Figure 69, impact obliquities are significant at standoffs less than 10 *feet*, but are insignificant at ranges greater than 100 *feet*. Most ballistic materials are relatively insensitive to impact obliquities less than 30 *degrees*, so that impact obliquity can be ignored for standoffs greater than the largest wall dimension.

4. Target Response Model

The perforation response of the wall is modeled using empirical perforation models such as those provided in the *PCDM*. Currently implemented models include a sand perforation model (Equations (VI-71) through (VI-74) in the *PCDM*) and the standard equations for ballistic materials. The perforation model for sand and THOR models for materials 1 through 17 are taken directly from the Air Force *PCDM*. The THOR models for the ballistic composites presented in Table 22 were derived under this project using the data discussed in Section II.

The perforation model derivations assume standard shapes for the penetrating fragment. Standard fragment shapes encountered in ballistic analyses and testing, as illustrated

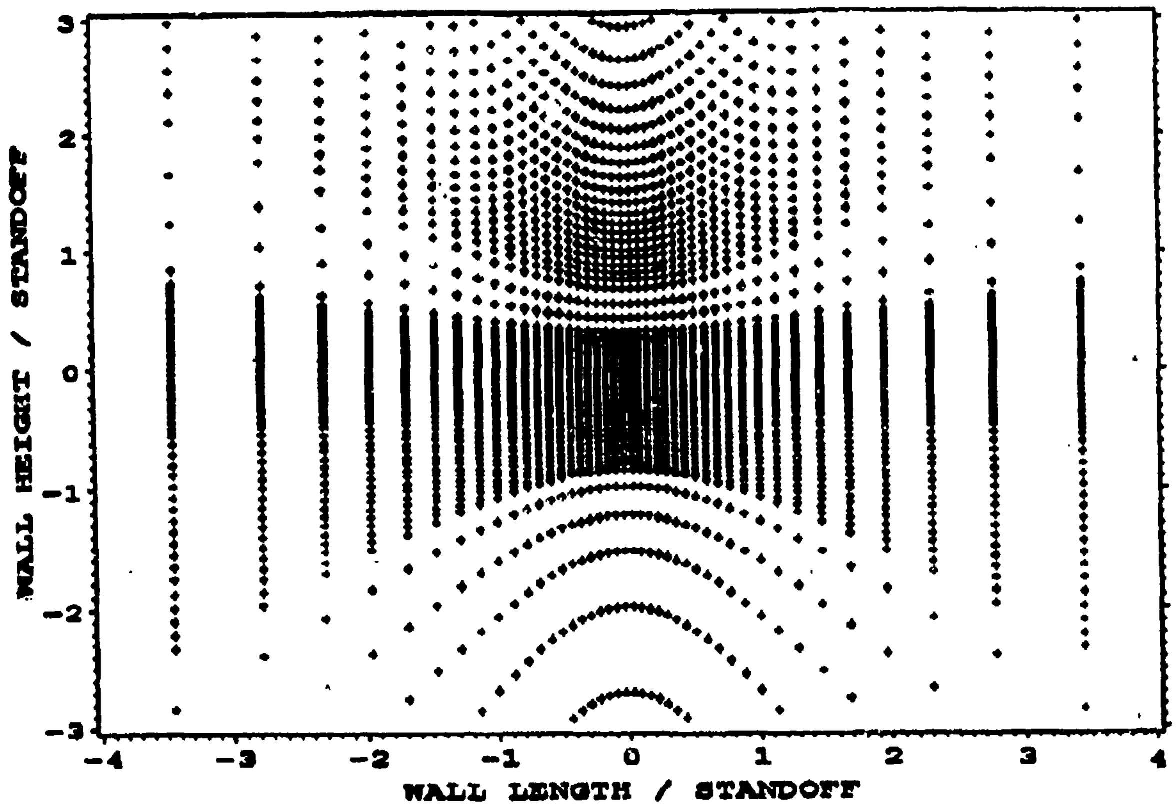


Figure 67. Mapping of Fragment Cells from a 1000-*Pound* GP Bomb onto Target Surface.

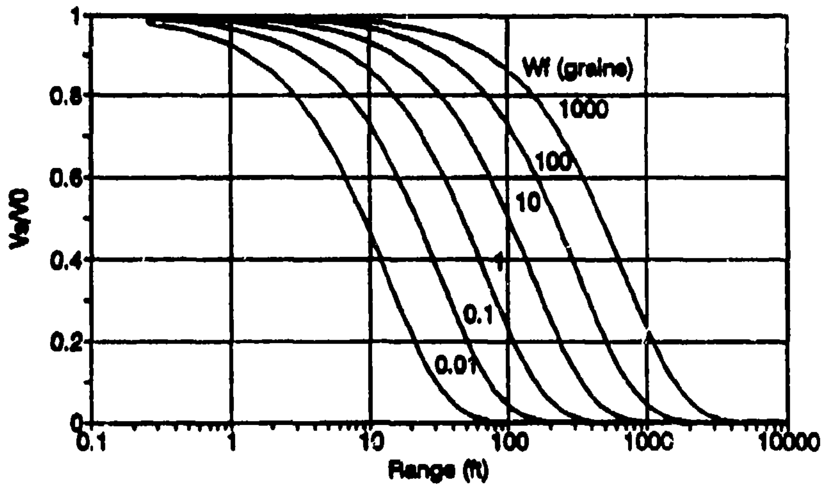


Figure 68. Fragment Velocity Decay Due to Drag.

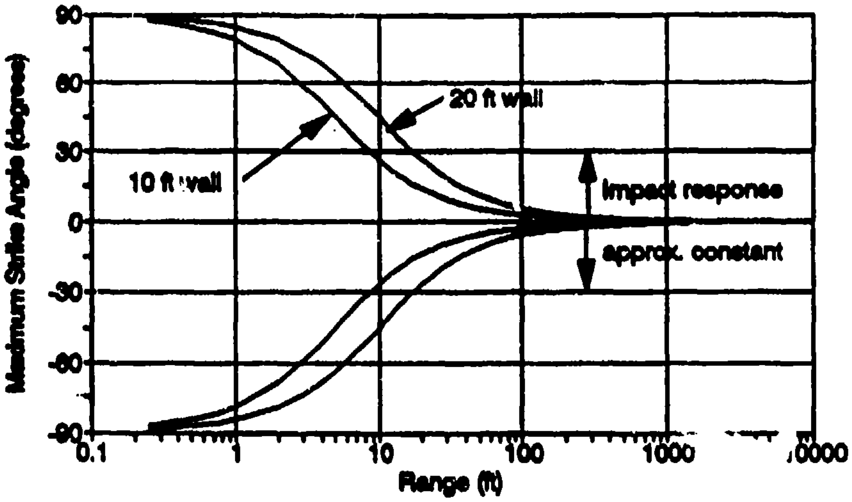


Figure 69. Fragment Impact Obliquity.

in Figure 70 include: (1) *PCDM* standard primary fragment (a right circular cylinder with a hemispherical nose); (2) fragment simulating projectiles (FSPS) (a right cylinder with 45-*degree* chamfers on nose end); and (3) right circular cylinders (RCCs). The *PCDM* standard fragment and FSP are normally encountered in heavy armor designs and analyses while RCCs are encountered in personnel protection and incapacitation studies.[1] These standard fragment shapes provide standards by which the relative performance of armor materials can be evaluated. Real fragments come in a variety of shapes that may be more or less lethal than the standard shapes. Consequently, the armor designs investigated in this study and developed under FOPS prototype design and testing need to be validated using fragments generated by real munitions.

The penetration depth of the *PCDM* standard primary fragment into soil is given by

$$x_f = k_{s1}\, W_f^{1/3} \ln\left(1 + k_{s2}\, v_s^2\right) \tag{10}$$

where x_f is the penetration depth into the soil (*inches*), W_f is the fragment weight (*pounds*), v_s is the fragment striking velocity (*feet/second*), and k_{s1} and k_{s2} are soil-dependent constants. For loose dry sand, k_{s1} = 5.06 *inch/pound*$^{1/3}$ and k_{s2} = 38 *second*^{2}/*feet*^{2}. Setting the penetration depth equal to the soil thickness and solving for the fragment striking velocity gives

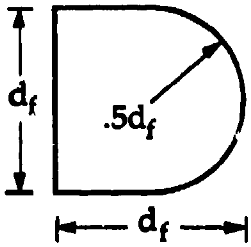
$$v_p = \sqrt{\left(\exp\left(t_s/k_{s1}\, W_f^{1/3}\right) - 1\right)/k_{s2}} \tag{11}$$

where t_s is the thickness of the soil (*inches*).

The residual velocity of fragments that perforate a layer of soil is estimated by

[1]Cubes are also frequently encountered in personnel casualty studies.

Air Force
Protective Construction Design Manual



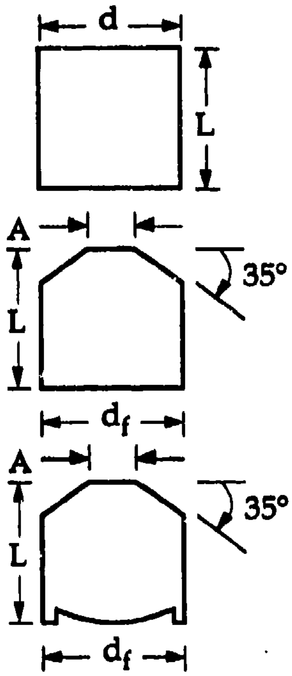
Diameter: $d_f = \left(\frac{24}{5\pi}\frac{W_f}{\gamma_f}\right)^{1/3}$

Caliber Density: $D = \frac{W_f}{d_f^3}$

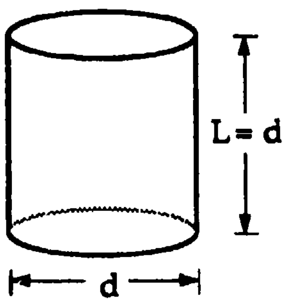
Caliber: $\eta = r_o/d_f$

MTL *Lightweight Armor Design Handbook*

Wgt/(gr)	Dimensions (in)		
	A	d_f	L
1.35	--	0.100	0.087
2.65	--	0.125	0.110
5.85	0.070	0.150	0.175
17	0.100	0.215	0.250
44	0.136	0.296	0.348
147	0.206	0.445	0.523
207	0.224	0.495	0.582
830	0.365	0.784	0.912



NRDEC
Personnel
Protection



$d_f = \left(\frac{4}{\pi}\frac{W_f}{\gamma_f}\right)^{1/3}$

Figure 70. Standard Fragment-Simulating Projectiles.

$$v_r = v_s\left(1 - \frac{t_s}{X_f}\right)^{0.555} \tag{12}$$

where v_r is the residual fragment velocity.

The THOR equations for ballistic perforation are the result of Project THOR conducted by the U.S. Army Ballistic Research Laboratory in the early 1950s. The THOR equation for ballistic limit velocity v_p, is

$$v_p = 10^{C_1}(tA_{f_1})^{\alpha_1}(7000W_f)^{\beta_1}(\sec\theta)^{\gamma_1} \tag{13}$$

where t is the target plate thickness (*inches*), A_f is the average impact area of the fragment (presented area) (*inches*^{2}), and W_f is the fragment weight (*pounds*), and θ is the impact obliquity (*degrees*). The factor 7000 in front of W_f is a conversion from pounds to grains. C_1, α_1, β_1, and γ_1 are empirical constants. Similarly, the THOR equation for residual velocity is

$$v_r = v_s - 10^{C_2}(tA_f)^{\alpha_2}(7000W_f)^{\beta_2}(\sec\theta)^{\gamma_2}v_s^{\lambda_2} \tag{14}$$

where v_s is the fragment striking velocity (*fps*) and C_2, α_2, β_2, γ_2, and λ_2 are empirical constants.

Table 21 presents the THOR empirical constants for seventeen materials often encountered in ballistic analyses [Drake, *et. al.*]. To supplement these data, THOR fits were developed for several of the modern ballistic fabrics (Kevlar® and Spectra®) and composite panels (Kevlar® 29 and KM2, S2/HJ1, and Spectra®) using data supplied by the manufacturers. Table 22 summarizes the empirical constants for these fits. The test data used in developing these fits assume standard fragment simulating projectile (FSP) shapes and collinear impact.[1]

a. Kevlar® and Spectra® Fabrics

Figure 71 plots the THOR equation fits for the Kevlar® and Spectra® fabrics. These fits are based on data provided by Allied Signal, Inc., for 1.01 to 1.26 *psf* areal density soft armor subjected to right circular cylinder FSPs (2, 4, 16, and 64 *grains*) [Allied-Signal, 1992]. The Kevlar® fabric was a 1500-*denier* basket weave while the Spectra® 1000 was a 650-*denier* plain weave. Spectra Shield™ is a cross-ply fabric laminate. The THOR equation fits the data quite well; however, the SAFE analyses require extrapolation of these data to high areal densities and larger fragment weights. Hence, SAFE results will require verification testing during prototype design and development.

[1]By collinear impact, we mean that the vector extending from the center of mass in the fragment to the nose of the fragment lies on the same line as the velocity vector of the fragment and that the fragment is not tumbling at the time of impact.

TABLE 21. THOR EQUATION FITS FOR VARIOUS BALLISTICS MATERIALS [Drake, *et al.*, 1989].

Material	C_1	α_1	β_1	γ_1	C_2	α_2	β_2	γ_2	λ_2
1. Magnesium	6.349	1.004	-1.076	0.966	6.904	1.092	-1.170	1.050	-0.087
2. Aluminum (2024-T3)	6.186	0.903	-0.941	1.098	7.047	1.029	-1.072	1.251	-0.139
3. Cast Iron	10.153	2.186	-2.204	2.156	4.840	1.042	-1.051	1.028	0.523
4. Titanium	7.552	1.325	-1.314	1.643	6.292	1.103	-1.095	1.369	0.167
5. Face Hard. Steel	7.694	1.191	-1.397	1.747	4.356	0.674	-0.791	0.989	0.434
6. Mild Homog. Steel	6.523	0.906	-0.963	1.286	6.399	0.889	-0.945	1.262	0.019
7. Hard Homog. Steel	6.601	0.906	-0.963	1.286	6.475	-0.889	-0.945	1.262	0.019
8. Copper	10.065	3.476	-3.687	4.270	2.785	0.678	-0.730	0.846	0.802
9. Lead	10.955	2.735	-2.753	3.590	1.999	0.499	-0.502	0.655	0.818
10. Tuballoy	14.773	3.393	-3.510	5.037	2.537	0.583	-0.603	0.865	0.828
11. Unbonded Nylon	5.006	0.719	-0.563	-0.852	5.816	0.835	-0.654	0.990	-0.162
12. Bonded Nylon	7.689	1.883	-1.593	1.222	4.672	1.144	-0.968	0.743	0.392
13. Lexan	7.329	1.814	-1.652	1.948	2.908	0.720	-0.657	0.773	0.603
14. Plexiglass as Cast	6.913	1.377	-1.634	1.415	5.243	1.044	-1.035	1.073	0.242
15. Stretched Plexiglass	11.468	3.537	-2.871	2.274	3.605	1.112	-0.903	0.715	0.686
16. Doron	5.581	0.750	-0.745	0.673	7.600	1.021	-1.014	0.917	-0.362
17. Bullet-Resistant Glass	6.991	1.316	-1.351	1.289	3.743	0.705	-0.723	0.690	0.465

TABLE 22. THOR EQUATION FITS FOR MODERN BALLISTICS FABRICS AND COMPOSITES.

Material	Unit Weight	THOR Constants			
	(pounds/feet^3)	C_1	α_1	β_1	γ_1
Fabrics					
Kevlar®	43.4	4.922	0.5650	-0.5272	-
Spectra® 1000	36.3	4.610	0.4384	-0.4384	-
Spectra Shield™	36.3	4.775	0.4950	-0.4950	-
Panels					
Kevlar®					
- K29 Standard	75.6	5.950	0.8550	-0.8824	0.4265
- K29 Special	75.6	5.980	0.8550	-0.8824	-
- KM2	75.6	6.060	0.8550	-0.8824	-
Spectra®					
- Spectra® 1000	60.4	4.906	0.5278	-0.4519	-
- Spectra Shield™	60.4	5.587	0.7119	-0.6923	-
- Combined	60.4	5.234	0.6390	-0.5945	-
S2-Glass	119.2	6.253	0.8939	-0.9316	-

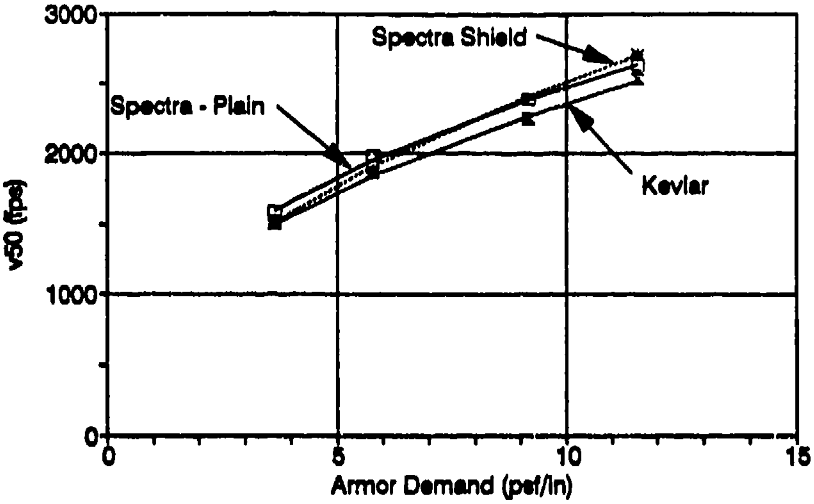


Figure 71. THOR Equation Fits for Kevlar® and Spectra® Fabrics.

b. Kevlar® Composite Panels

Three THOR equation fits are provided for Kevlar® composite panels: (1) K29 using standard processing; (2) K29 using special processing; and (3) KM2 using special processing. K29/Special and KM2/Special data were taken from a DuPont Product Bulletin on KM2 [DuPont, 1992]. The K29/Special data is for a 1500-*denier* 2×2 basket weave while the KM2/Special data is for a 850-*denier* plain weave. Both special processing systems used a 18 *percent* Phenolic/PVB resin system. Projectiles included 2, 4, and 16-*grain* RCCs and a 17-*grain* FSP. The K29/Special was supplemented with data provided by Owens Corning Fiberglass for 44-*grain* (0.30 *cal*) and 207-*grain* (0.50 *cal*) FSPs. The K29/Standard data was provided by Allied Signal [Allied Signal, 1992 and NDa]. Figure 72 compares the three THOR equation fits with data for the K29/Special and KM2/Special composite panels. As with the fabrics, the SAFE analyses represent an extrapolation of the data and will require verificaton during prototype development.

c. Spectra® Composite Panels

Figure 73 compares the THOR equation fits for Spectra® panels. THOR equation fits were developed for Spectra® 1000 and Spectra Shield™ composite panels using data provided by Allied-Signal in [Allied Signal, 1992 and NDa]. Test projectiles included 17-*grain* (0.22 *cal*), 44-*grain* (0.30 *cal*), and 207-*grain* (0.50 *cal*) FSPs. Panel areal densities ranged from 1 to 2 *psf* for the Spectra® 1000 and from 1 to 5 *psf* for the Spectra Shield™. Due to the differences in areal density ranges, a combined THOR equation fit was also developed and used in the SAFE analyses.

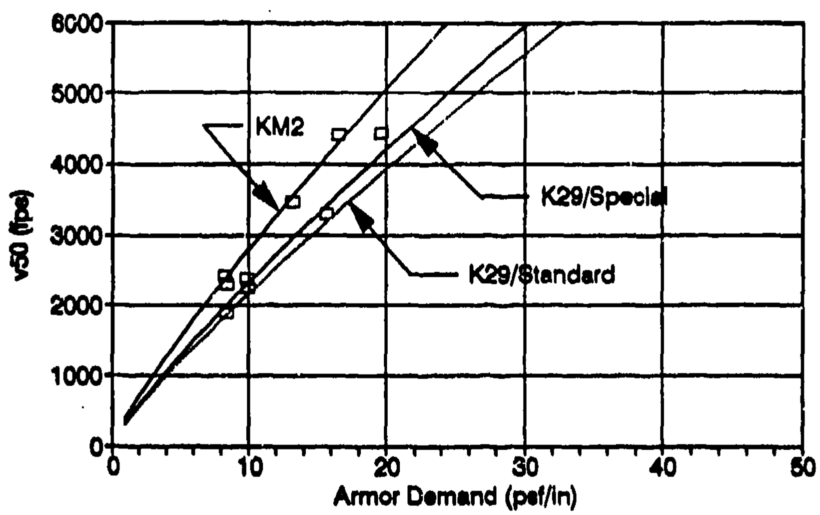


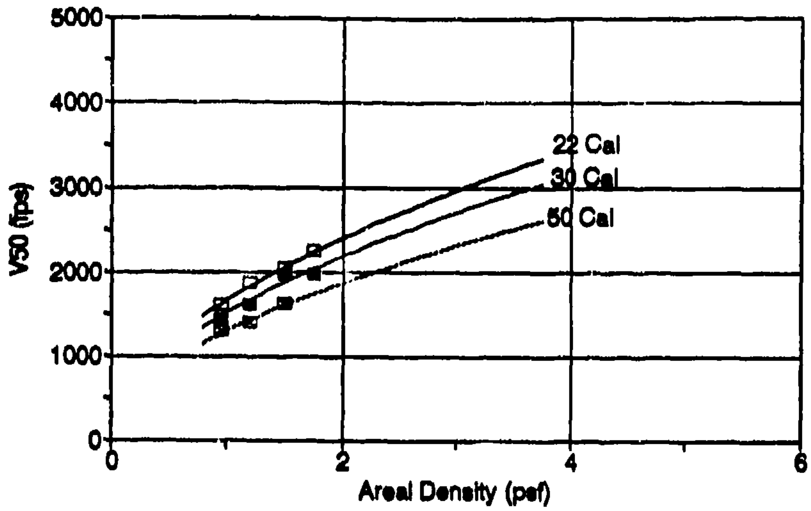
Figure 72. THOR Equation Fits for Kevlar® Composite Panels.

d. S2/HJ1 Composite Panels

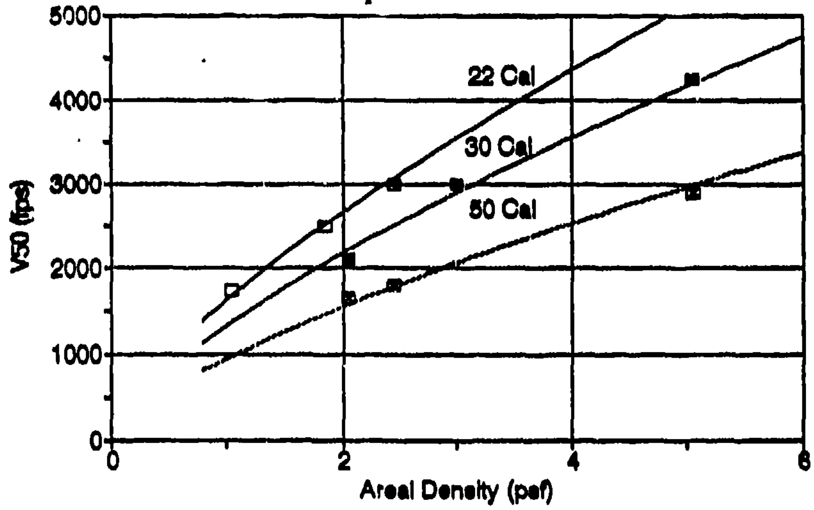
S2-glass composite panels utilize either E780CM (polyester resin) or Hexcel HJ1, a phenolic resin. The HJ1 resin system provides superior ballistic protection and is more environmentally resistant: hence, only the HJ1 resin system was considered in the analyses. Data used in developing the THOR equation fit was provided by Owens-Corning Fiberglass [OCF, NDa] Panel areal densities ranged from 2 to 22 *psf* and projectiles included 44-*grain* (0.30 *cal*), 207-*grain* (0.50 *cal*), and 230-*grain* (20-*mm*) FSPs. This data collection was the most extensive and had the broadest range of all the composite materials considered. Figure 74 plots the THOR equation fit against the data.

e. Composite Panel Summary

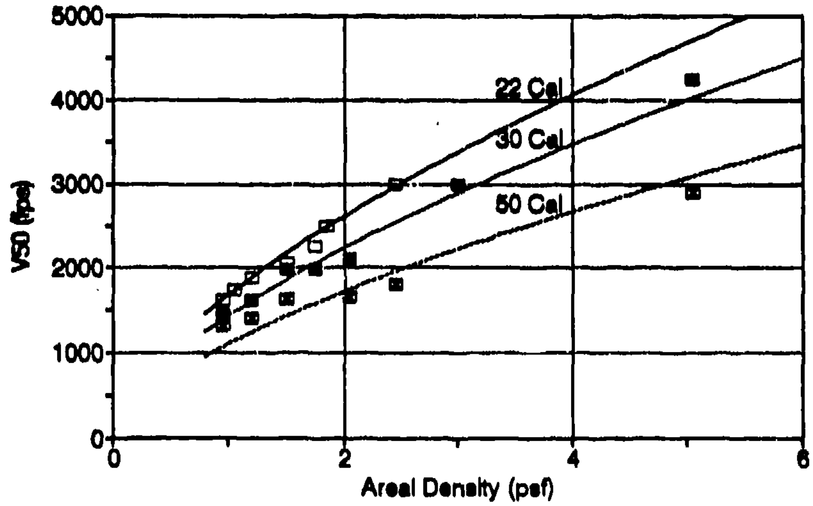
Figure 75 plots the THOR perforation models for Kevlar® (KM2/Special and K29/Standard), Spectra® (combined), and S2/HJ1 for impact by 44-*grain* (0.30 *cal*), 207-*grain* (0.50 *cal*), and 830-*grain* (20-*mm*) FSPs. These plots provide a relative measure of the ballistic performance of these composite panels. Against the 44-*grain* FSP, KM2 provides the best protection with Spectra®, S2/HJ1, and K29/Standard providing comparable levels of performance. The relative performance of Spectra® becomes comparable to KM2 as the fragment size is increased to 207 *grains* and exceeds that of KM2 for the 830-*grain* fragment. Performance levels for S2/HJ1 and K29/Standard are nearly identical for all three FSPs. Based on these comparisons, we expect that KM2 and Spectra® will provide the best protection against fragment impact and that the performance of S2-glass and K29/Standard will lag behind that of KM2 and Spectra®.



a. Spectra® 1000



b. Spectra Shield™



c. Combined

Figure /3. THOR Equation Fits for Spectra® Composite Panels.

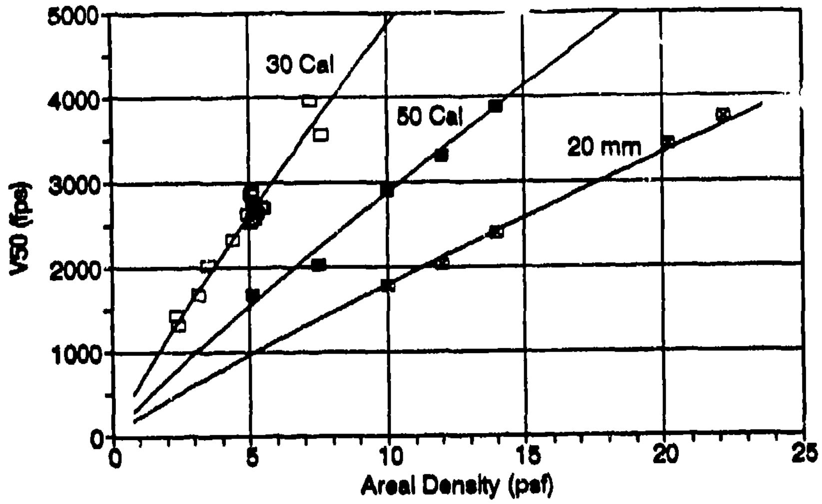


Figure 74. THOR Equation Fit for S2/HJ1 Composite Panels.

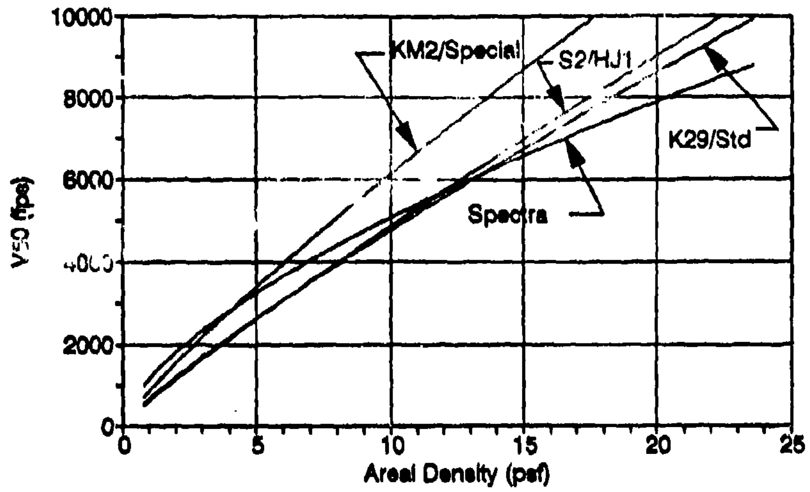
G. FRAGMENT HARDENING — SAFE RESULTS

In this section we present the results of SAFE analyses of the hardening concepts previously identified in Section III.C. Two attack scenarios are considered as illustrated in Figure 76: (1) lateral threats for each threat weapon detonated at standoff on the ground surface and horizontally centered on the wall; and (2) an overhead threat from an artillery shell burst. For the lateral threats, a static burst with the weapon axis oriented vertically and nose tangent to the ground is assumed. For the overhead artillery threat, the artillery shell is assumed incoming on a trajectory oriented 39 *degrees* from the horizontal with a velocity of 1200 *fps* [Drake, *et. al.*, 1991].

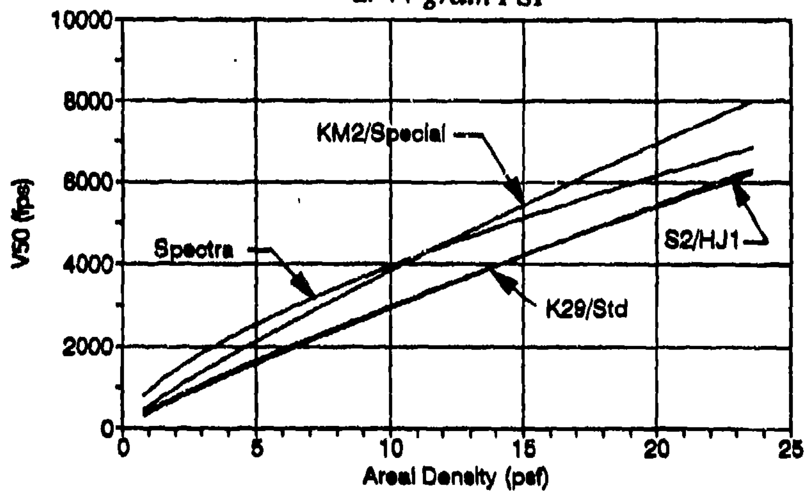
The hardening concepts are divided into three generic classes: (1) fabric hardening upgrades (*e.g.* ballistic blankets); (2) composite panels (integral, infill, or external shields); and (3) field expedient hardening methods (*e.g.* soil berms and bins). For each hardening class, two wall sizes are assessed: (1) a small shelter wall with dimensions 8 *feet* high × 32 *feet* long, and (2) a large shelter wall with dimensions 15 *feet* high and 80 *feet* long. Both vertical and slanted walls are considered. The slope of the slanted walls is selected as representative of the lower portion of a cylindrical arch cross-section as illustrated in Figure 77. For each wall, hardening concept, and threat weapon the number of perforations per 10 $feet^2$ of surface area as a function of range and areal density of armor material is assessed.

1. Fabric Hardening Upgrades

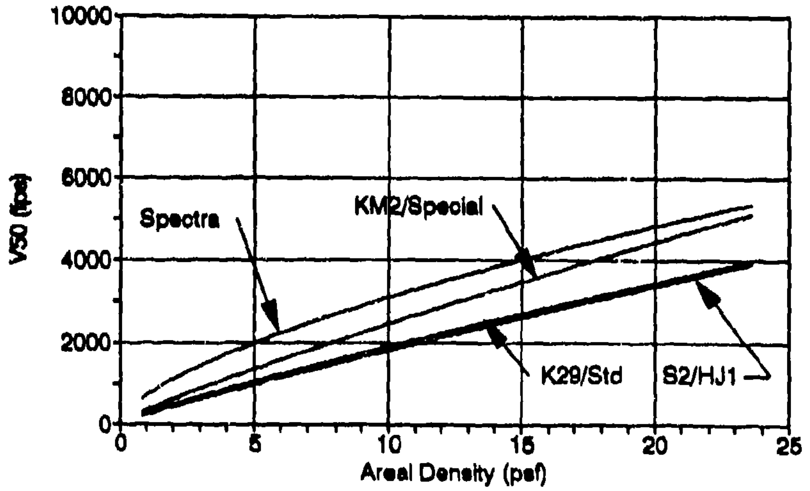
Two fabric hardening upgrades are assessed: (1) Kevlar® ballistic blankets and (2) Spectra® ballistic blankets. SAFE analyses of small walls constructed of these materials (areal densities of 2, 4, and 8 *psf*) were performed for each of the six threat weapons.



a. 44-*grain* FSP

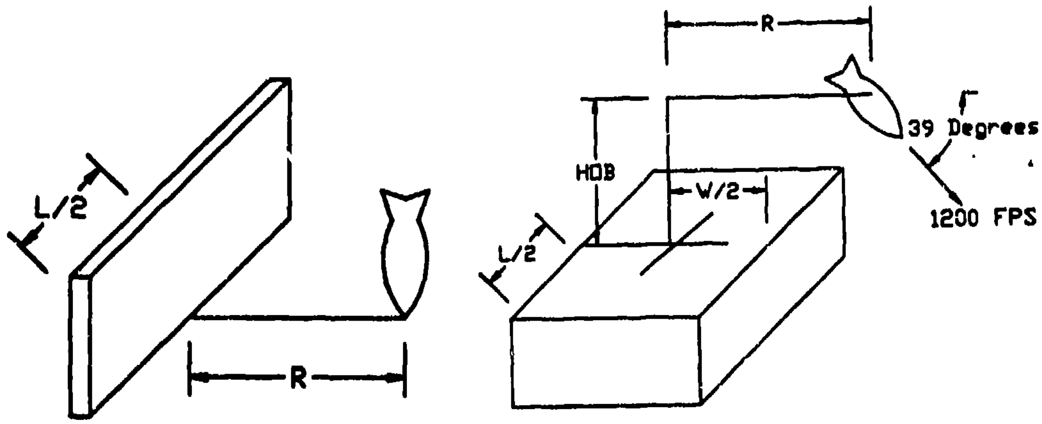


b. 207-*grain* FSP



c. 830-*grain* FSP

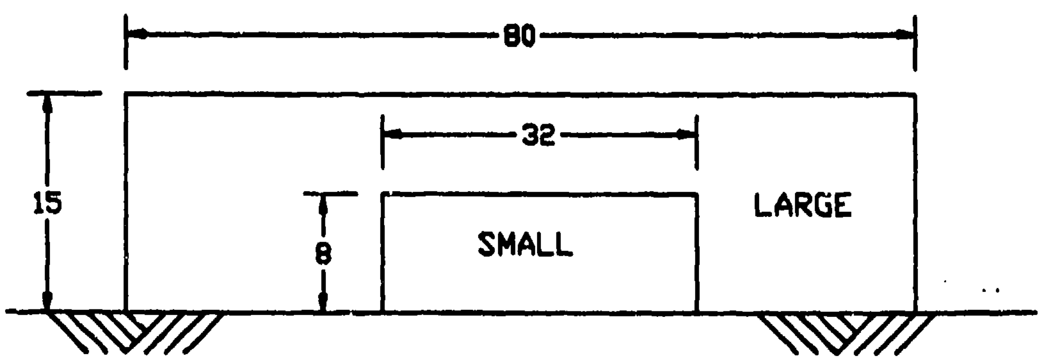
Figure 75. Relative Ballistic Performance of Spectra®, Kevlar®, and S2-Glass Monolithic Composite Panels.



a. Lateral Threats

b. Overhead Threat

Figure 76. Threat Scenarios Assessed in SAFE Hardening Analysis.



a. Vertical Walls

Small Wall

Large Wall

b. Slanted Walls

Figure 77. Wall Configurations Assumed in SAFE Hardening Assessment.

Figures 78 and 79 present the SAFE results for the two fabric hardening upgrades. Shown are the number of perforations per 10 *feet*^{2} of vertical projected wall area (*i.e.*, the perforation density) as a function of standoff (20 to 400 *feet* in general) for each threat weapon. Four curves are provided for each weapon: one for each areal density (2, 4, and 8 *psf*) and one for an unprotected (0 *psf*) wall with no inherent resistance to perforation. For the 40-*mm* A/C cannon, both fabrics are effective in reducing the number of fragment perforations to near zero at very small standoffs with 2 to 4 *psf* of material. Both fabrics are also effective in reducing the number of perforations for the cluster munition and 122-*mm* rocket; however, standoffs of 30 to 90 *feet* are required, depending on the areal density of ballistic material employed. Standoff requirements for the 152/155-*mm* artillery, 250-*pound* missile, and 1000-*pound* bomb are significantly more severe, as expected.

Two general trends are noted in the results: (1) the performance of the two materials is very similar with the Spectra® being slightly better, and (2) the greatest rate of decrease occurs between wall areal densities of 0 and 2 *psf*. Table 23 and Figure 80 further illustrate these observations. Table 23 lists the weapon standoffs required for a perforation areal density of one perforation per 10 *feet*^{2} of wall surface. Maximum surface projection of personnel can be conservatively taken as 10 *feet*^{2} and not all hits within this area would be fatal; thus, this perforation areal density provides a lower bound estimate of the range where personnel have a reasonable chance of survival. Figure 80 plots the required standoffs for this protection level normalized to the standoff required if no protection is provided. Table 23 and Figure 80 show that the standoffs required for the two materials to achieve this protection level are nearly identical, with Spectra® having a slight edge. The range decrease is greatest between no protection and 1 *psf* of protection.[1] For example, a standoff reduction of 113 *feet* is obtained for the 1000-*pound* bomb for 1 *psf* of either material, compared to an average of 14.3 (Kevlar®) and 15.6 (Spectra®) *feet* for each additional *psf* of material above 1 *psf*.

Table 24 and Figures 81 through 83 repeat the analyses for the large shelter wall. In general, results are comparable to those for the small shelter wall. Required standoffs for the large shelter walls are smaller for the 1000-*pound* bomb, 40-*mm* A/C cannon, and cluster munition and larger for the 152/155-mm artillery, 122-*mm* rocket, and 250-*pound* missile. Figure 84 shows that these differences in required standoff reflect the effect of the munition fragment spray pattern on the number of fragment impacts. Shown are the fragment impact mapping for the cluster munition ($R = 100$ *feet*) and artillery shell ($R = 200$ *feet*) for the large and small shelter walls. Each cross in Figure 84 represents the impact location for the midpoint of a munition cell.[2] Hence, the frequency of crosses is a measure of the relative number of impacts on the wall. For the cluster munition, the beam spray is nearly horizontal, providing a uniform

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[1]These curves actually have a characteristic horizontal "s"-shape; range reductions are high initially as a little material is added and again at areal densities capable of stopping nearly all fragments. This effect is shown more clearly in Appendix H for the small shelter wall with rigid panels.

[2]Munition cells were uniformly distributed circumferentially and along the munition axis.

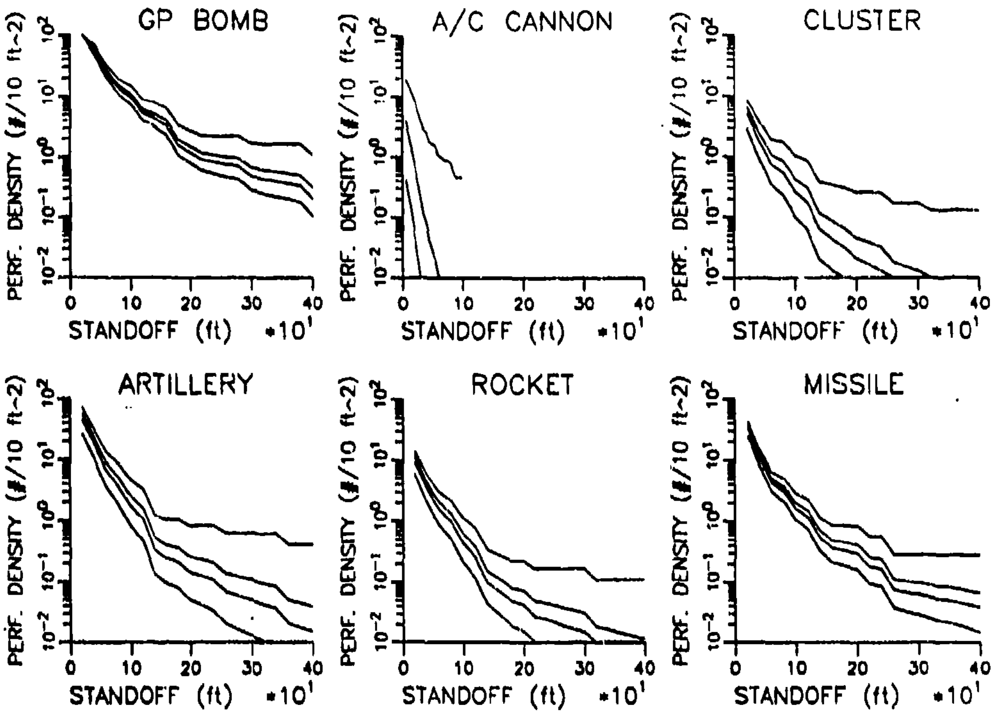


Figure 78. SAFE Perforation Densities for Small Shelter Wall — Kevlar® Fabric.

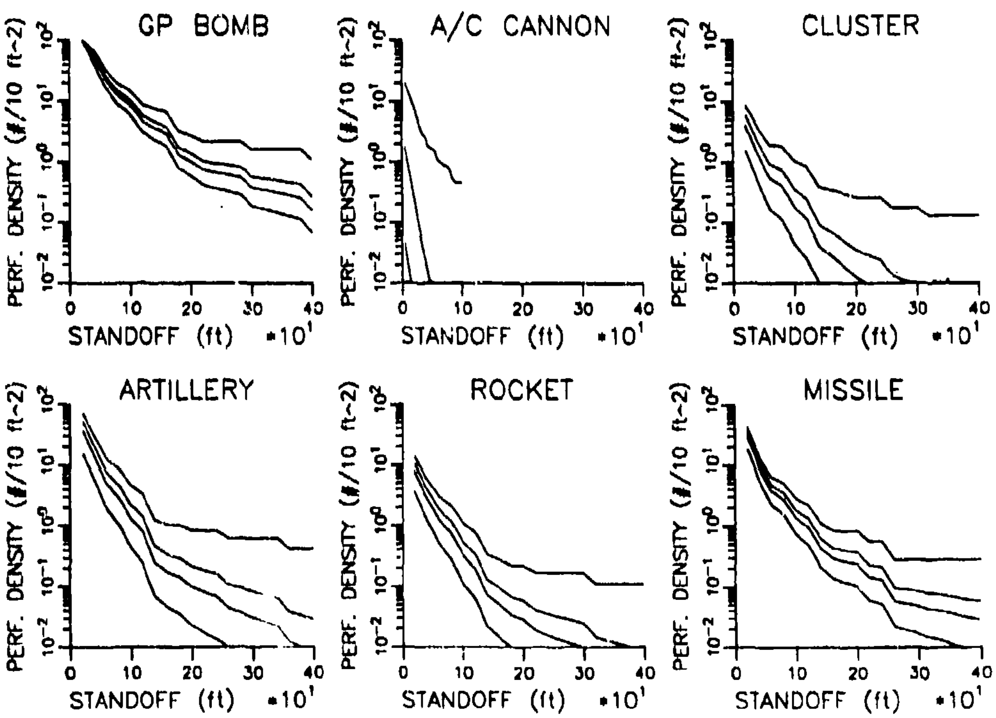


Figure 79. SAFE Perforation Densities for Small Shelter Wall — Spectra® Fabric.

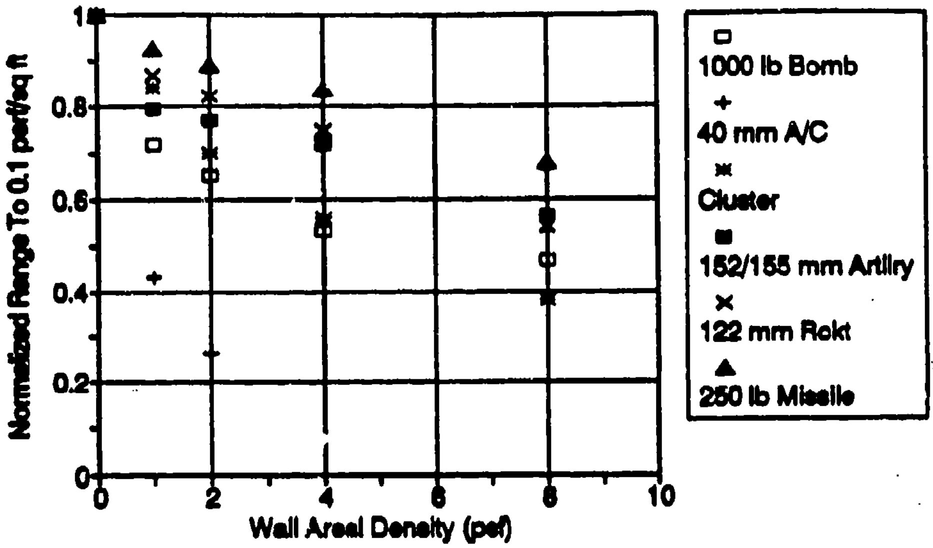
TABLE 23. REQUIRED STANDOFFS FOR 0.1 PERFORATIONS/*FOOT*^{2} — SMALL SHELTER FABRIC WALLS.

Material Density (*psf*)	Range to 1 Perforation in 10 *Feet*^{2}					
	1000-*lb* Bomb	40-*mm* A/C Cannon	Cluster Munition	152/155-*mm* Artillery	122-*mm* Rocket	250-*lb* Missile
Unprotected	400	65	100	170	107	147
Kevlar®						
- 1 *psf*	287	28	84	135	93	136
- 2 *psf*	260	17	70	131	88	131
- 4 *psf*	213	-	56	122	80	123
- 8 *psf*	187	-	38	96	58	100
- rate (*ft*/*psf*)	14.3	11	6.6	5.6	5.0	5.1
Spectra®						
- 1 *psf*	287	19	80	134	92	133
- 2 *psf*	230	10	60	129	86	129
- 4 *psf*	200	-	48	112	70	120
- 8 *psf*	178	-	30	80	46	92
- rate (*ft*/*psf*)	15.6	9	7.1	7.7	6.6	5.8

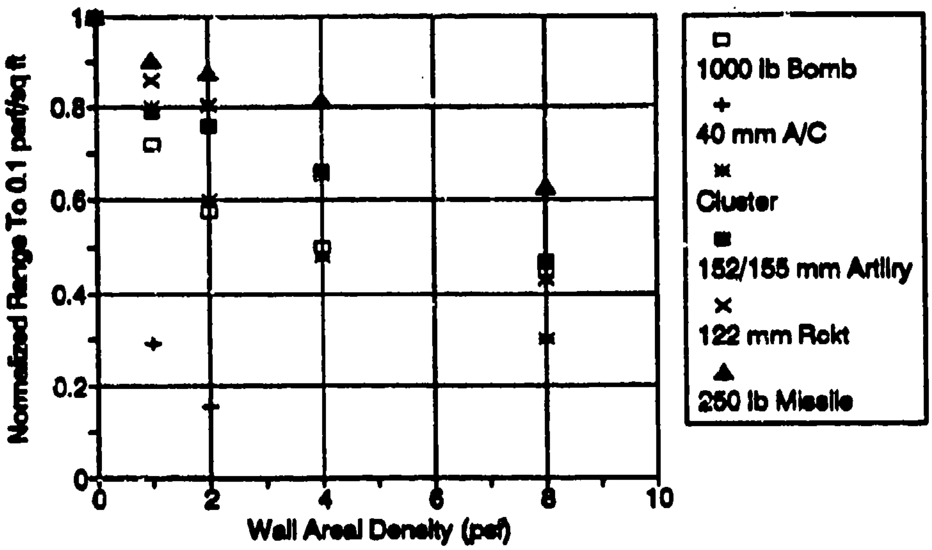
TABLE 24. REQUIRED STANDOFFS FOR 0.1 PERFORATIONS/*FOOT*^{2} — LARGE SHELTER FABRIC WALLS.

Material Density (*psf*)	Range to 1 Perforation in 10 *Feet*^{2} [a]					
	1000-*lb* Bomb	40-*mm* A/C Cannon	Cluster Munition	152/155-*mm* Artillery	122-*mm* Rocket	250-*lb* Missile
Unprotected	393	57	70	213	113	180
Kevlar®						
- 1 *psf*	288	17	51	160	87	148
- 2 *psf*	260	4	47	150	78	140
- 4 *psf*	213	-	38	127	58	120
- 8 *psf*	187	-	23	100	40	100
- rate (*ft*/*psf*)	14.4	13	4	8.6	5.3	6.8
Spectra®						
- 1 *psf*	254	7	50	157	80	145
- 2 *psf*	248	-	40	144	67	130
- 4 *psf*	220	-	31	114	51	112
- 8 *psf*	180	-	-	73	27	80
- rate (*ft*/*psf*)	10.6	7	6.3	12	7.6	9.3

a "--" entry means standoff was less than 20 *feet* (5 *feet* for 40-*mm* A/C cannon).



a. Kevlar®



b. Spectra®

Figure 80. Normalized Range Reductions for Small Shelter Wall — Fabric Upgrades.

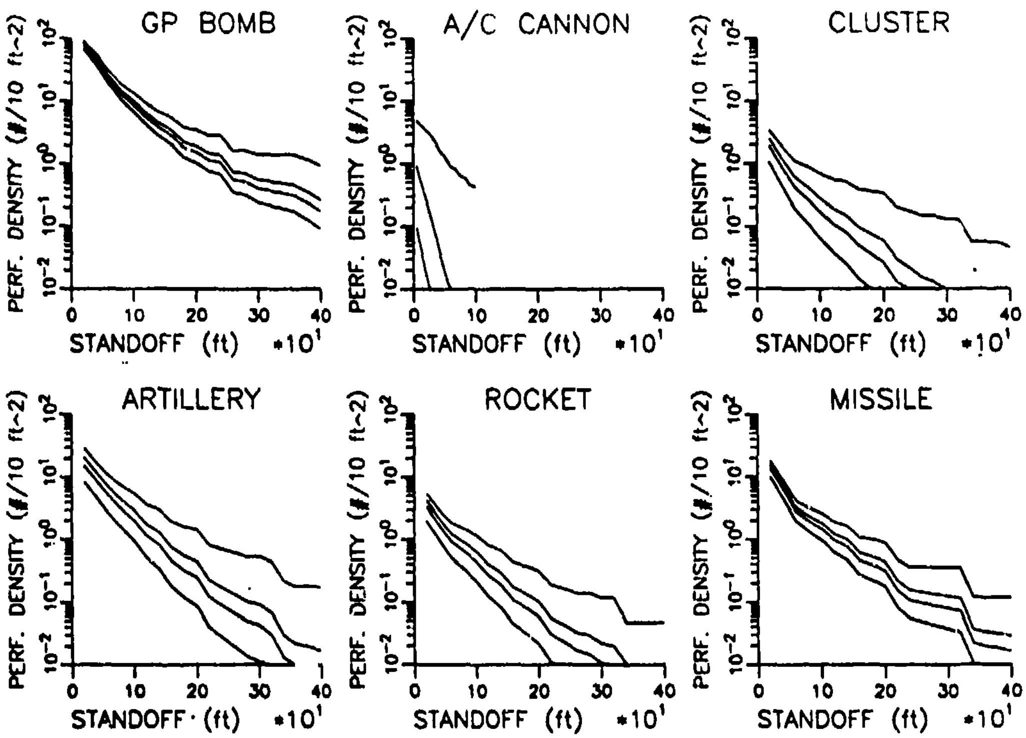


Figure 81. SAFE Perforation Densities for Large Shelter Wall — Kevlar® Fabric.

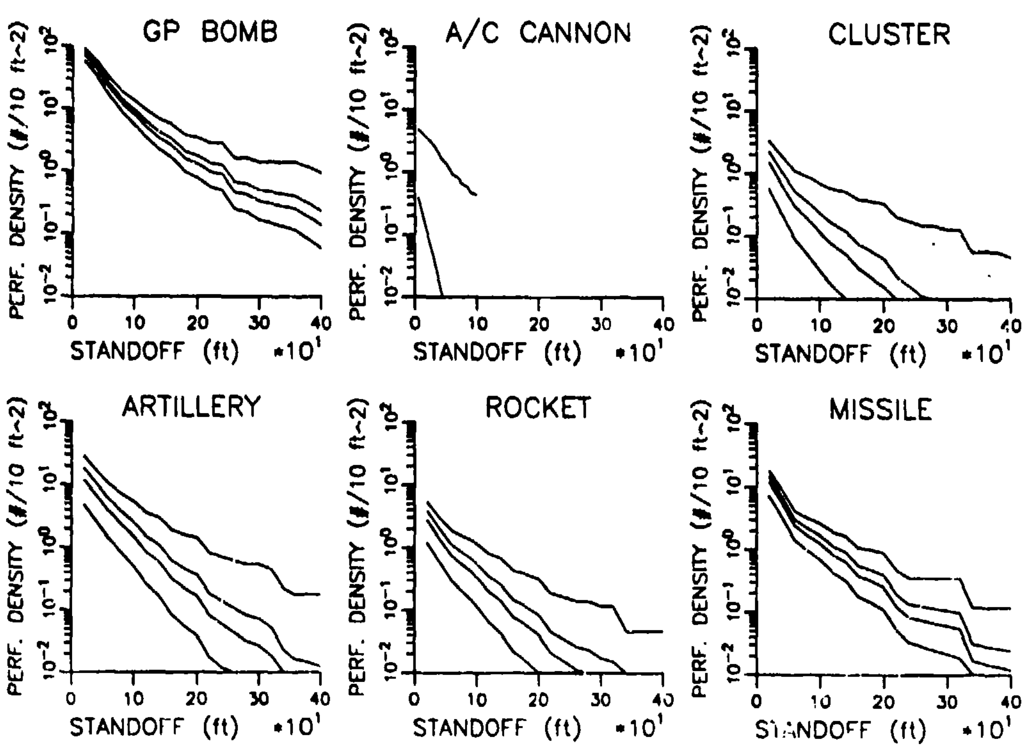
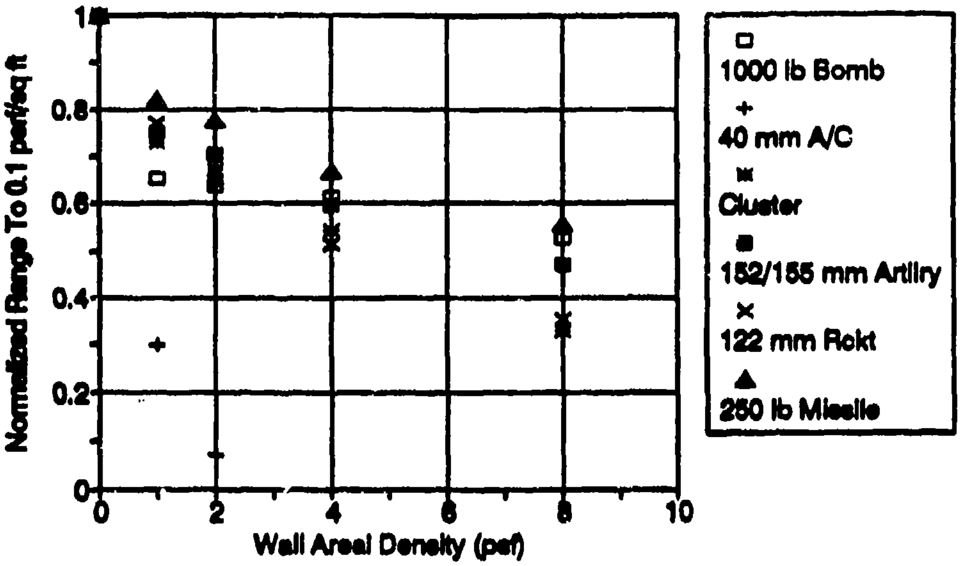
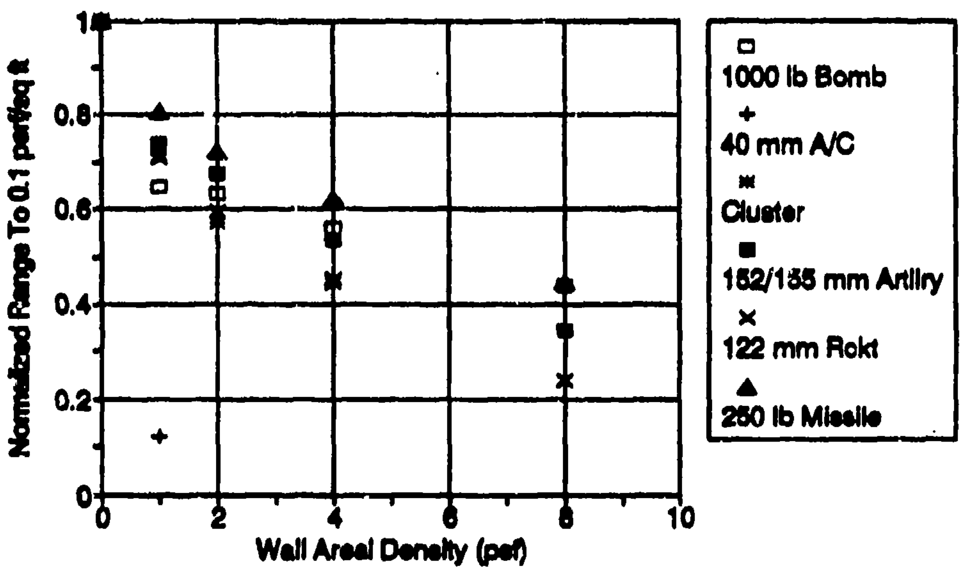


Figure 82. SAFE Perforation Densities for Large Shelter Wall — Spectra® Fabric.



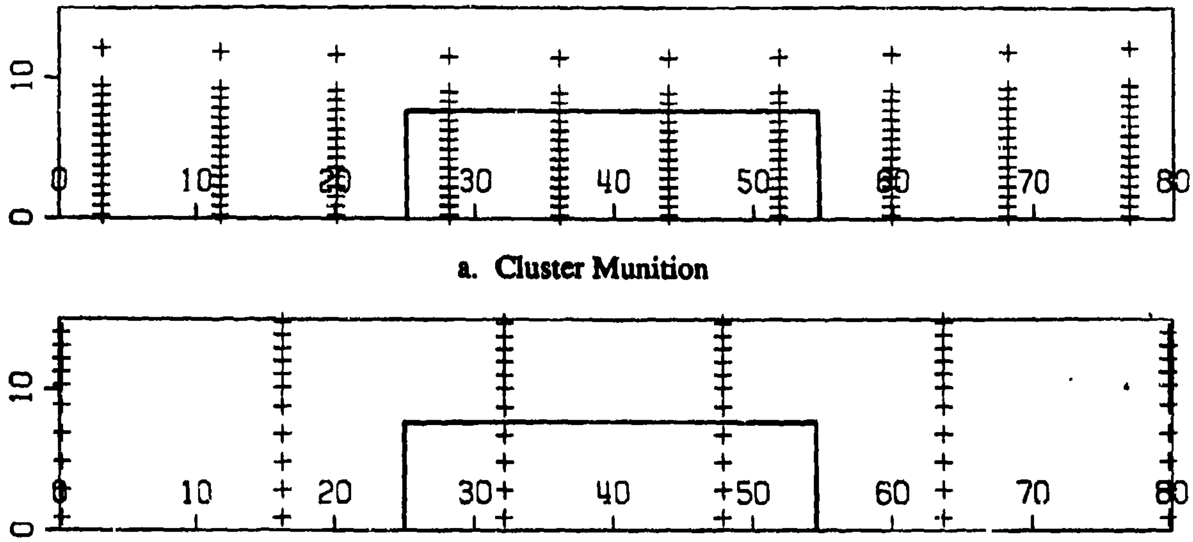
a. Kevlar® Fabric



b. Spectra® Fabric

Figure 83. Normalized Range Reductions for Large Shelter Wall — Fabric Upgrades.

fragment spray over an elevation of 9 to 10 *feet*. Thus, the density of impacts in the incremental wall area for the large shelter is much lower than that for the small shelter wall, and the required standoff is reduced. The spray pattern for the artillery shell, on the other hand, is skewed towards its tail, such that the main beam spray is elevated and misses the small shelter wall. Impact densities are larger in the incremental area for the large shelter wall; consequently, the average number of impacts for the large shelter wall and the required standoff increase.



a. Cluster Munition

b. Artillery Shell

Figure 84. Fragment Impact Mapping for Large and Small Shelter Walls.

2. Panel Hardening Upgrades

As discussed in Section III.B panel hardening upgrades include integrally hardened sandwich composite panels, infill panels added between frame members in fabric shelters, and externally mounted shields. Materials considered include aluminum, Kevlar® (KM2), Spectra®, and S2/HJ1. Panels may be either sandwich construction (integral and infill) or solid. Since the perforation models for the Kevlar®, Spectra®, and S2/HJ1 materials do not include residual velocity, core construction and layering effects are not considered and all panels are analyzed as being monolithic in construction.

Figures 85 through 94 and Tables 25 and 26 present the SAFE results for the small and large shelter walls with composite panels. The number of perforations versus weapon standoff curves and the range reductions for 0.1 *perforations/foot*^{2} for the Kevlar®, Spectra®, and S2/HJ1 composite materials are very similar to each other and to the Kevlar® and Spectra® fabrics previously discussed. Kevlar® performance is slightly better than the Spectra® and S2-glass; however, we do not consider this difference to be significant. These materials are as effective as twice the areal density of aluminum.

SAFE calculations were also performed for slanted small and large shelter panel walls as previously illustrated in Figure 77. The perforation curves for these walls are similar to those for the vertical shelter wall. Tables 27 and 28 summarize required standoffs to 0.1 *perforation/feet*^{2} for the slanted shelter walls. Comparison of these results with those for the vertical walls in Tables 25 and 26 (small and large shelter wall, respectively) show that the slanted walls are more effective in reducing standoffs than the vertical walls. This improved performance is most pronounced for small (40-*mm* A/C cannon cluster munition, and artillery shell) and intermediate

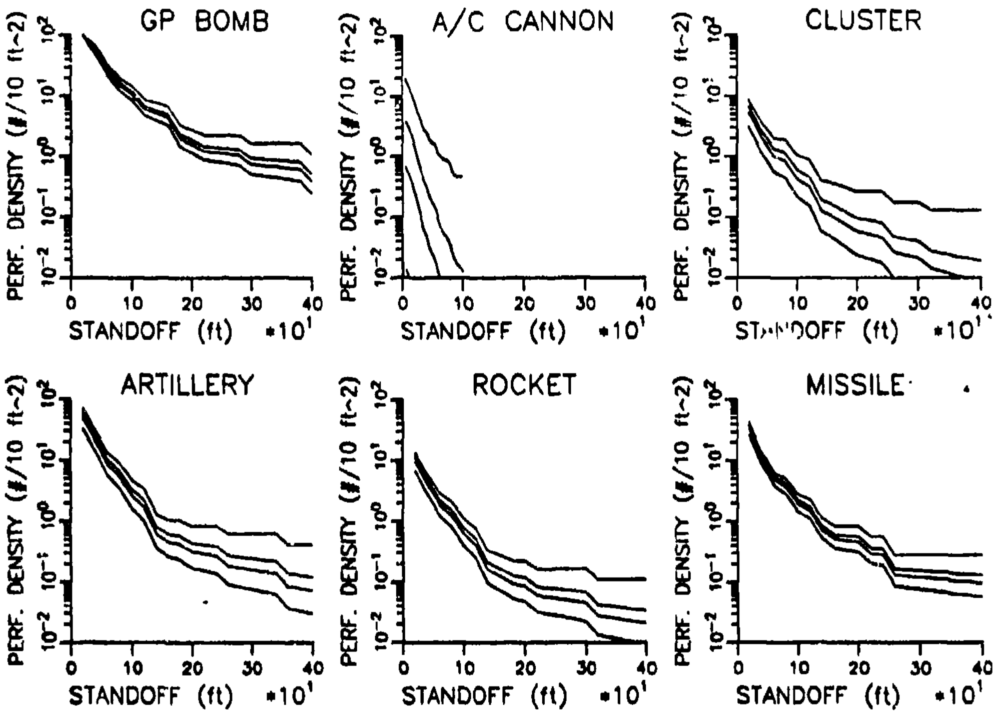


Figure 85. SAFE Perforation Densities for Small Shelter Wall — Aluminum Panels.

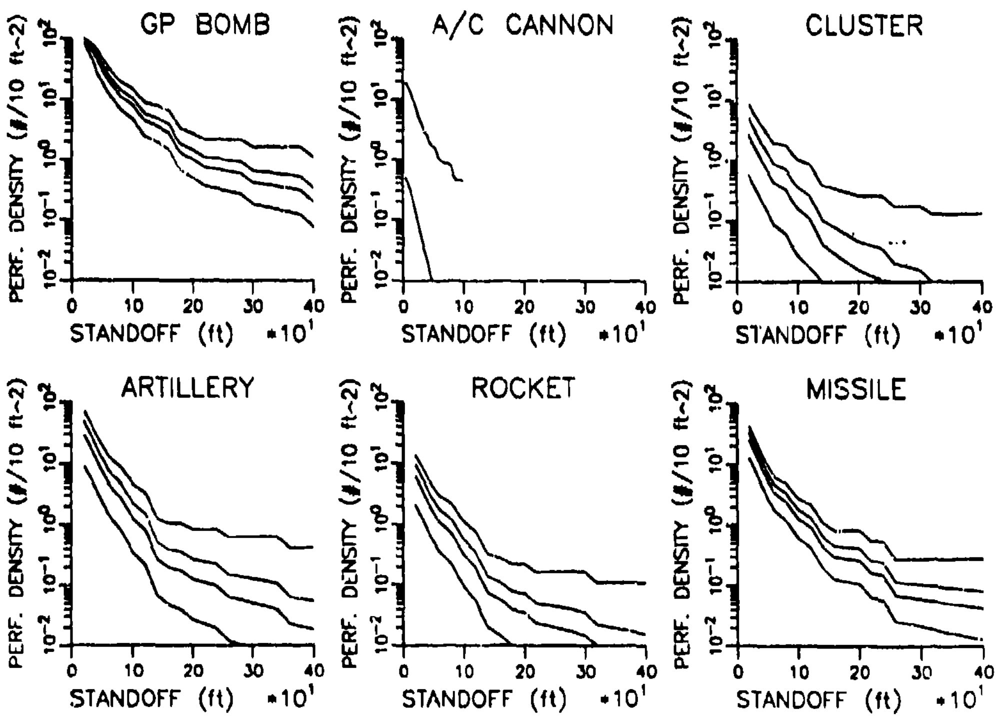


Figure 86. SAFE Perforation Densities for Small Shelter Wall — KM2 Panels.

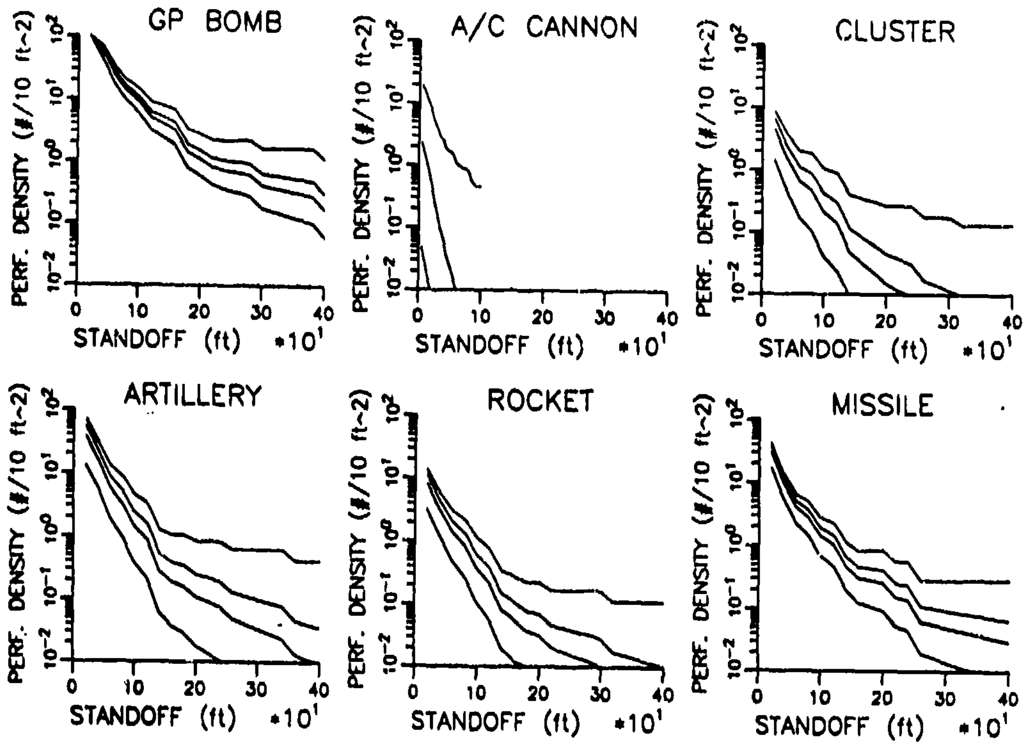


Figure 87. SAFE Perforation Densities for Small Shelter Wall — Spectra® Panels.

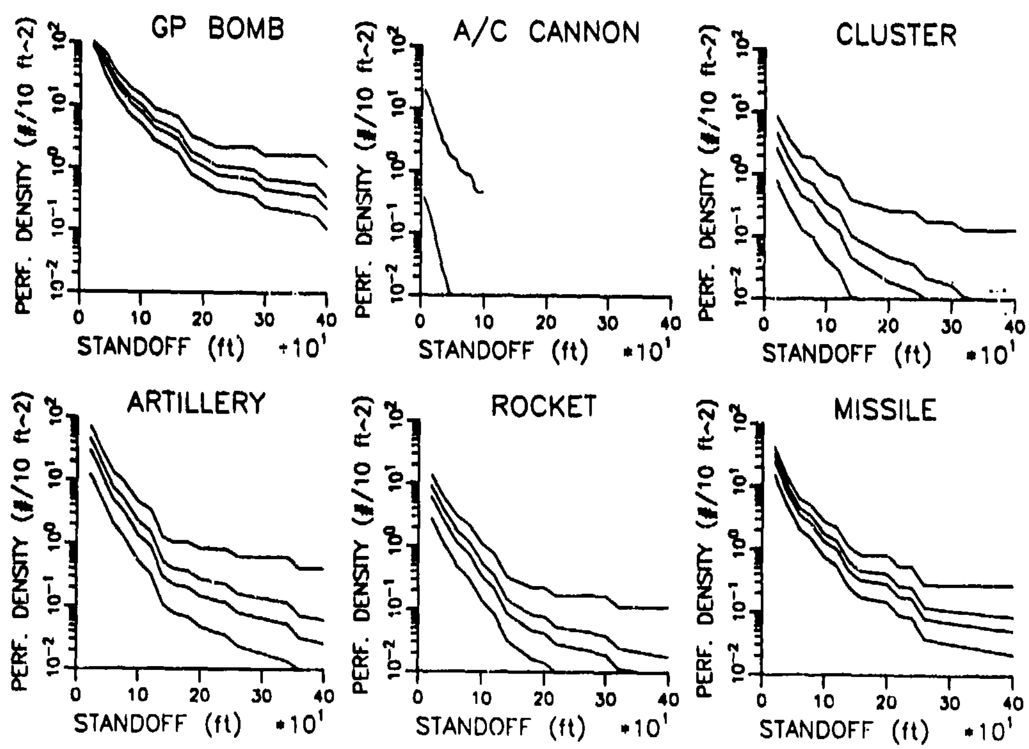


Figure 88. SAFE Perforation Densities for Small Shelter Wall — S2/HJ1 Panels.

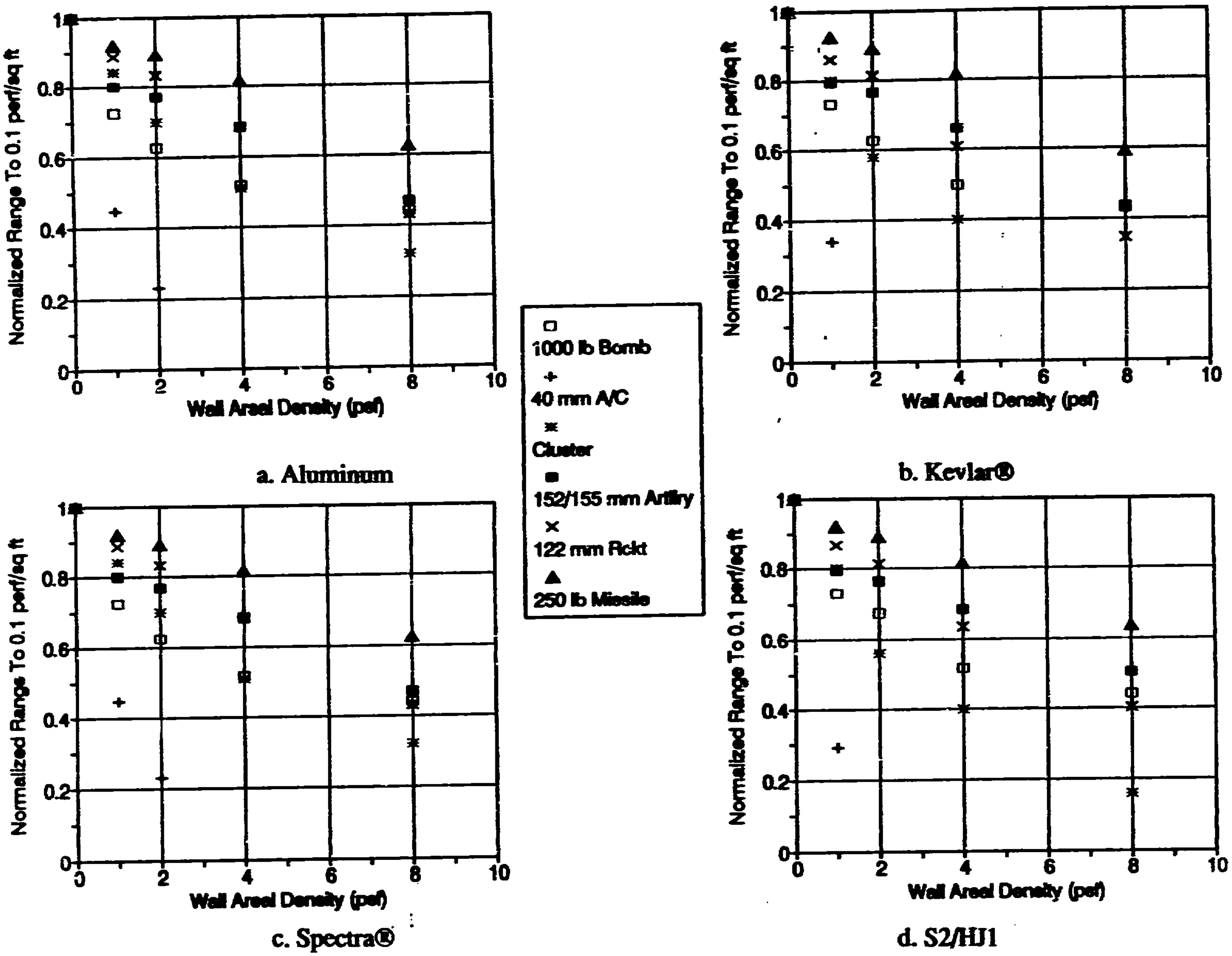


Figure 89. Normalized Range Reductions for Small Shelter Wall — Panels.

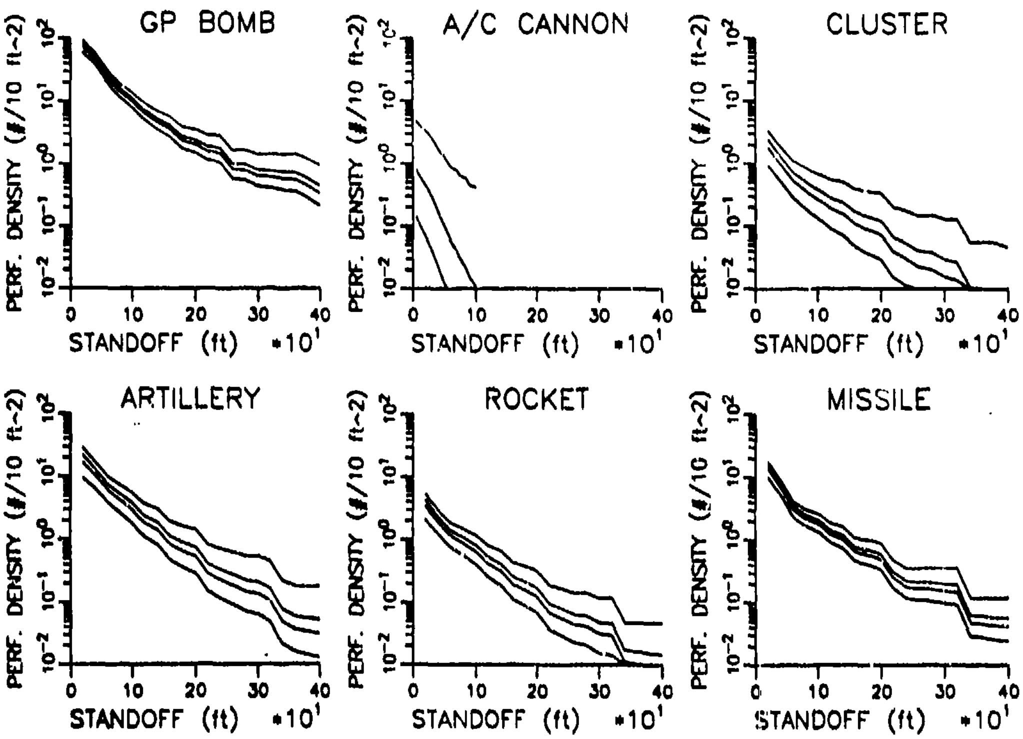


Figure 90. SAFE Perforation Densities for Large Shelter Wall — Aluminum Panels.

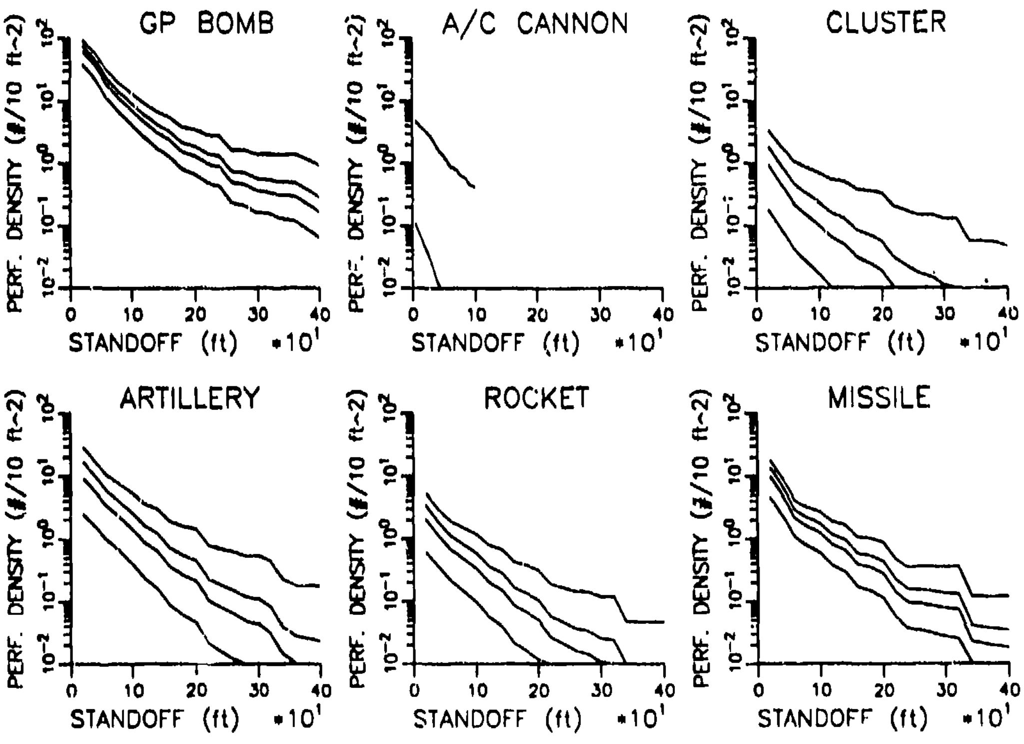


Figure 91. SAFE Perforation Densities for Large Shelter Wall — KM2 Panels.

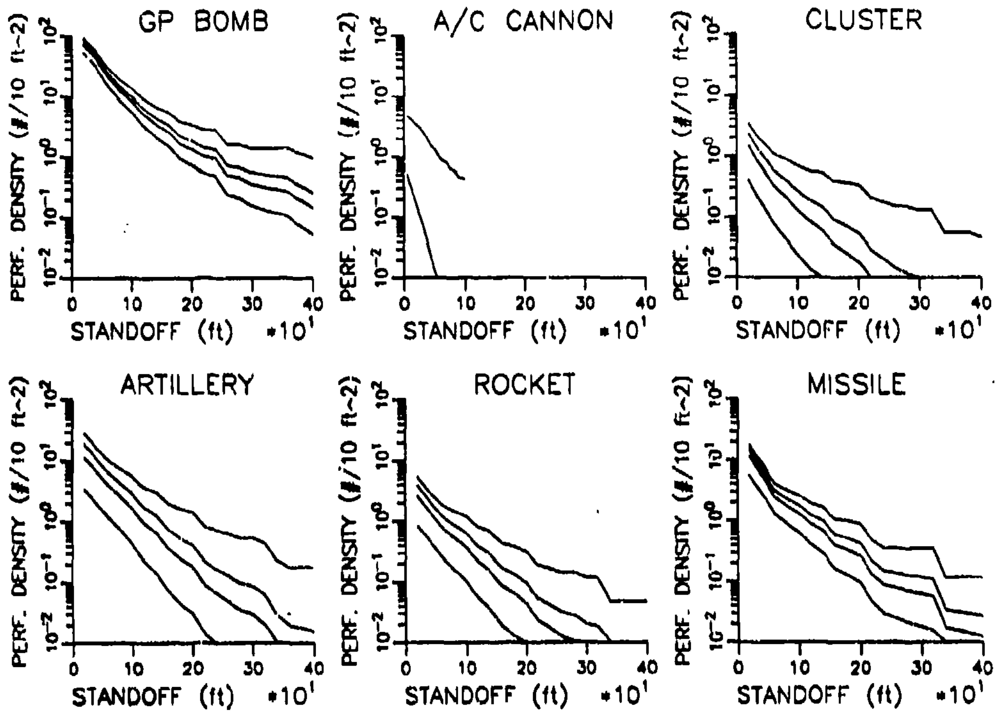


Figure 92. SAFE Perforation Densities for Large Shelter Wall — Spectra® Panels.

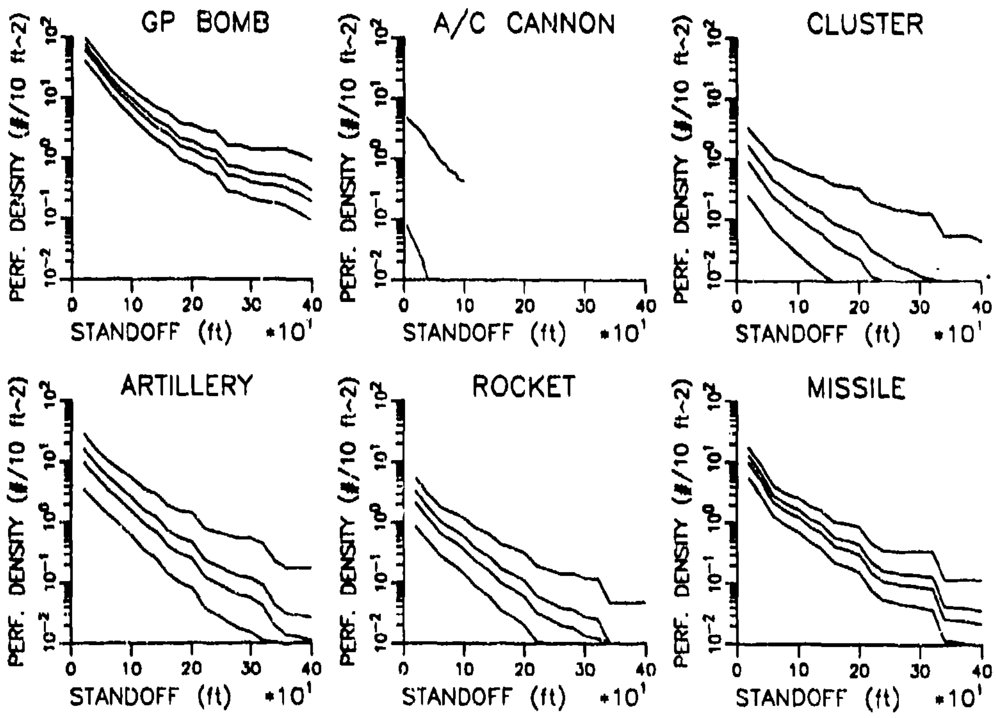


Figure 93. SAFE Perforation Densities for Large Shelter Wall — S2/HJ1 Panels.

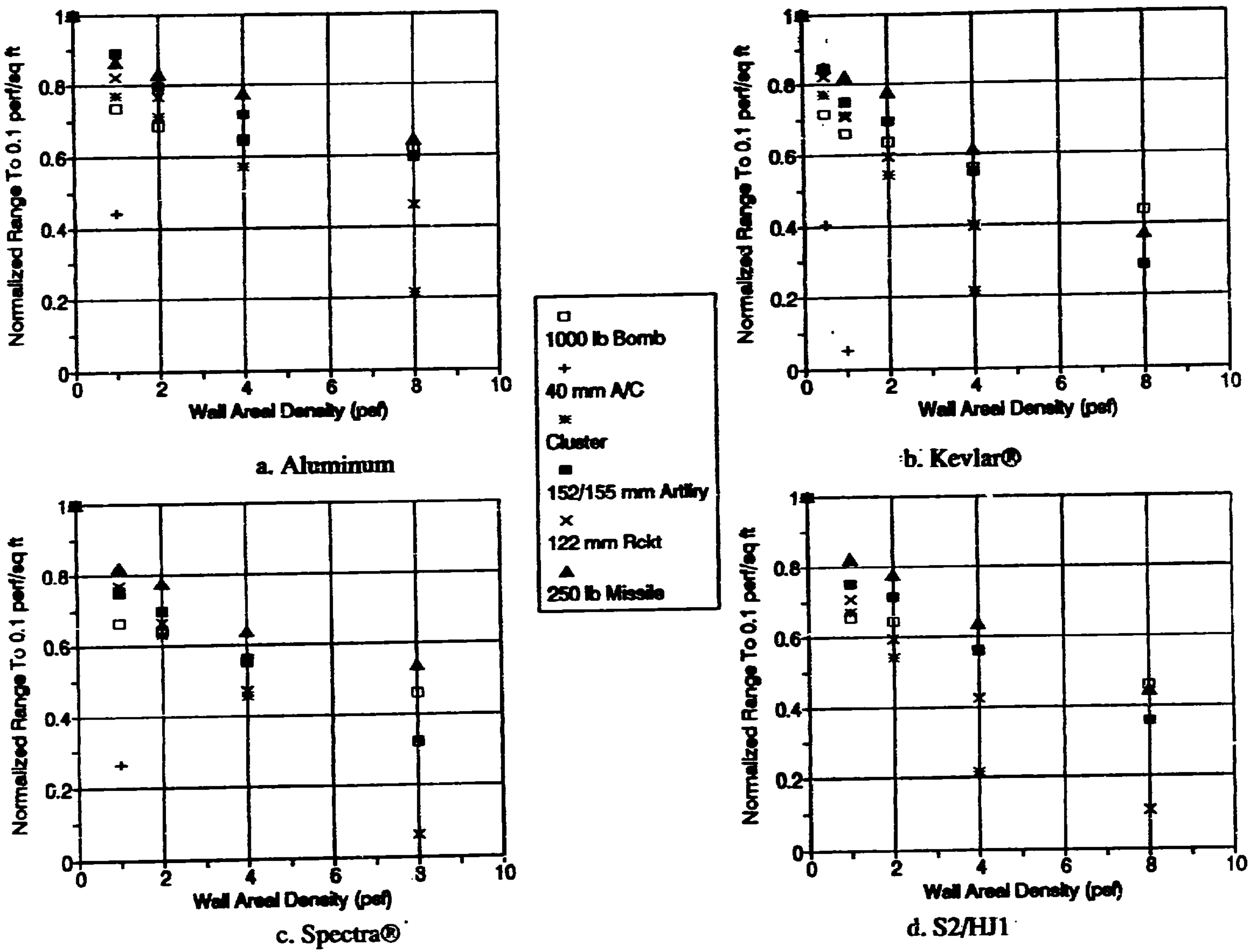


Figure 94. Normalized Range Reductions for Large Shelter Wall — Panels.

TABLE 25. REQUIRED STANDOFFS FOR 0.1 PERFORATIONS/*FOOT*^{2} — SMALL SHELTER PANEL WALLS.

Material Density (*psf*)	Range to 1 Perforation in 10 *Feet*^{2} [a]					
	1000-*lb* Bomb	40-*mm* A/C Cannon	Cluster Munition	152/155-*mm* Artillery	122-*mm* Rocket	250-*lb* Missile
Unprotected	400	65	100	170	107	147
Aluminum						
- 1 *psf*	320	35	90	139	98	138
- 2 *psf*	290	25	84	137	95	135
- 4 *psf*	280	-	60	135	89	132
- 8 *psf*	213	-	47	120	75	123
- rate	15.3	10	6.1	2.7	3.3	2.14
Kevlar® KM2						
- 1 *psf*	293	22	80	135	92	136
- 2 *psf*	250	-	58	130	87	131
- 4 *psf*	200	-	40	112	65	120
- 8 *psf*	172	-	-	74	37	87
- rate	17.3	-	11.4	8.7	7.9	7.0
Spectra®						
- 1 *psf*	290	29	84	136	95	135
- 2 *psf*	250	15	70	131	89	131
- 4 *psf*	207	-	51	116	73	120
- 8 *psf*	176	-	32	80	46	92
- rate	16.3	14	7.4	8.0	7.0	6.1
S2 Glass						
- 1 *psf*	293	19	80	135	93	135
- 2 *psf*	270	-	56	130	87	131
- 4 *psf*	207	-	40	116	68	120
- 8 *psf*	176	-	16	86	43	94
- rate	16.7	-	9.1	7.0	7.1	5.8

[a] "--" entry means standoff was less than 20 *feet* (5 *feet* for 40-*mm* A/C cannon).

(122-*mm* rocket) weapon fragment threats and larger areal densities. The performance gain for the small weapons results from a combination of increased impact obliquity and fewer impacts (fragments hitting near the top of vertical wall barely miss the slanted wall). Performance differences for the GP bomb are small (approximately 1 to 5 *percent* for composites and 1 to 10 *percent* for aluminum).

3. Soil Bins/Berms Hardening Upgrades

Field expedient hardening methods, such as soil berms and soil bins, provide an excellent means of protecting structures and equipment from fragment impact. To evaluate the

TABLE 26. REQUIRED STANDOFFS FOR 0.1 PERFORATIONS/*FOOT*^{2} — LARGE SHELTER PANEL WALLS.

Material Density (*psf*)	Range to 1 Perforation in 10 *Feet*^{2} [a]					
	1000-*lb* Bomb	40-*mm* A/C Cannon	Cluster Munition	152/155-*mm* Artillery	122-*mm* Rocket	250-*lb* Missile
Unprotected	393	57	70	213	113	180
Aluminum						
- 1 *psf*	290	25	54	190	93	156
- 2 *psf*	270	-	50	170	87	150
- 4 *psf*	254	-	40	153	73	140
- 8 *psf*	244	-	15	127	52	116
- rate	6.6	-	5.6	9.0	5.9	5.7
Kevlar® KM2						
- 1 *psf*	260	3	50	160	80	148
- 2 *psf*	250	-	38	148	67	140
- 4 *psf*	220	-	15	117	45	110
- 8 *psf*	172	-	-	60	-	67
- rate	12.6	-	11.7	14.3	11.7	11.6
Spectra®						
- 1 *psf*	260	15	53	160	87	148
- 2 *psf*	250	-	44	148	75	140
- 4 *psf*	220	-	32	117	53	115
- 8 *psf*	180	-	-	68	7[b]	75
- rate	11.4	-	7.0	13.1	11.4	10.4
S2 Glass						
- 1 *psf*	258	-	47	160	80	148
- 2 *psf*	253	-	38	152	67	140
- 4 *psf*	220	-	15	120	48	115
- 8 *psf*	180	-	-	76	12[c]	80
- rate	11.1	-	10.7	12.0	9.7	9.7

[a] "--" entry means standoff was less than 20 *feet* (5 *feet* for 40-*mm* A/C cannon).
[b] Results Extrapolated for 8 *psf*.
[c] Results extrapolated for 8 *psf*.

performance of integral or upgradeable hardening of the shelter using modern ballistic fabrics and composite panels relative to these expedient hardening methods, SAFE analyses are performed for soil-hardened small and large shelter walls. The analyses consider only the effect of the soil in stopping the fragments (*i.e.*, the skin perforation resistance is not included for soil bins). Soil thickness is varied in 1-*foot* increments from 1 to 4 *feet*. Since the analyses assume a constant wall thickness, the results are more applicable to soil bins than to berms, which would have a sloped face and variable soil thickness. In reviewing these results, one should keep in mind that 12 *inches* of soil equates to an areal density of approximately 100 *psf*, which exceeds the areal densities considered in the fabric and panel upgrades by an order of magnitude.

TABLE 27. REQUIRED STANDOFFS FOR 0.1 PERFORATIONS/$FOOT^2$ — SLANTED SMALL PANEL WALLS.

Material Density (*psf*)	Range to 1 Perforation in 10 *Feet*² [a]					
	1000-*lb* Bomb	40-*mm* A/C Cannon	Cluster Munition	152/155-*mm* Artillery	122-*mm* Rocket	250-*lb* Missile
Unprotected	400	55	105	164	107	148
Aluminum						
- 1 *psf*	333	31	77	138	92	138
- 2 *psf*	294	17	70	136	84	136
- 4 *psf*	272	--	58	131	76	131
- 8 *psf*	204	--	39	112	62	120
- rate	18.4	14	5.4	3.7	4.3	2.6
Kevlar® KM2						
- 1 *psf*	291	7	69	135	82	135
- 2 *psf*	244	--	57	129	75	130
- 4 *psf*	190	--	38	103	59	114
- 8 *psf*	169	--	--	63	32	74
- rate	17.4	--	10.3	10.3	7.1	8.7
Spectra®						
psf	288	24	72	135	85	135
· .., f	240	7	60	130	77	130
- 4 *psf*	200	--	20	107	65	117
- 8 *psf*	172	--	--	67	37	78
- rate	16.6	7	17.3	9.7	6.8	8.1
S2 Glass						
- 1 *psf*	291	8	66	135	80	134
- 2 *psf*	252	--	56	129	75	130
- 4 *psf*	202	--	38	109	60	118
- 8 *psf*	162	--	--	73	38	80
- rate	18.4	--	9.3	8.6	6.0	7.7

[a] "--" entry means standoff was less than 20 *feet* (5 *feet* for 40-*mm* A/C cannon).

Figures 95 through 97 and Table 29 present the SAFE results for the soil hardening upgrades. As expected, the soil bin hardening upgrade is highly effective in defeating the fragment threat. Small antipersonnel/antimateriel weapons, such as the 40-*mm* A/C cannon, cluster munition, and 122-*mm* rocket, are easily defeated by 1 to 2 *feet* of soil. Considerable protection can also be obtained for the larger weapons, however, at substantially higher thicknesses and standoffs. For the artillery shell, approximately 3 *feet* of soil cover reduces required standoffs to near zero and between 4-5 *feet* of soil are required for the missile and GP bomb.

TABLE 28. REQUIRED STANDOFFS FOR 0.1 PERFORATIONS/*FOOT*^{2} — SLANTED LARGE SHELTER PANEL WALLS.

Material Density (*psf*)	Range to 1 Perforation in 10 *Feet*^{2} [a]					
	1000-*lb* Bomb	40-*mm* A/C Cannon	Cluster Munition	152/155-*mm* Artillery	122-*mm* Rocket	250-*lb* Missile
Unprotected	394	52	67	198	105	188
Aluminum						
- 1 *psf*	287	7	51	173	85	135
- 2 *psf*	258	--	42	154	75	130
- 4 *psf*	250	--	28	134	58	120
- 8 *psf*	216	--	--	105	32	100
- rate	10.1	--	7.7	9.7	7.6	5.0
Kevlar® KM2						
- 1 *psf*	257	--	44	152	75	129
- 2 *psf*	248	--	32	133	59	119
- 4 *psf*	213	--	--	103	36	98
- 8 *psf*	165	--	--	40	--	57
- rate	13.1	--	12.0	16.0	13	10.3
Spectra®						
- 1 *psf*	256	7	48	150	77	130
- 2 *psf*	247	--	38	133	64	120
- 4 *psf*	215	--	20	105	42	100
- 8 *psf*	171	--	--	44	--	60
- rate	12.1	--	9.3	15.1	11.7	100
S2 Glass						
- 1 *psf*	257	--	40	150	73	128
- 2 *psf*	249	--	30	133	58	119
- 4 *psf*	217	--	--	109	38	101
- 8 *psf*	173	--	--	60	--	67
- rate	12.0	--	10.0	12.8	11.7	8.7

[a] "--" entry means standoff was less than 20 *feet* (5 *feet* for 40-*mm* A/C cannon).

Figure 98 summarizes the relative protection provided by the composite panels and fabrics investigated. The number of fragment perforations is shown as a function of weapon standoff for a 1000-*pound* bomb detonated near a small shelter wall with 4 *psf* of ballistic material. The curves for no protection (*i.e.*, number of hits) and 2 *feet* of soil cover are also shown for comparison. The results show that all the composite materials, fabrics and blankets, provide comparable levels of protection. This protection is significantly greater than that provided by aluminum, and approaches that provided by 2 *feet* of soil at large standoffs.

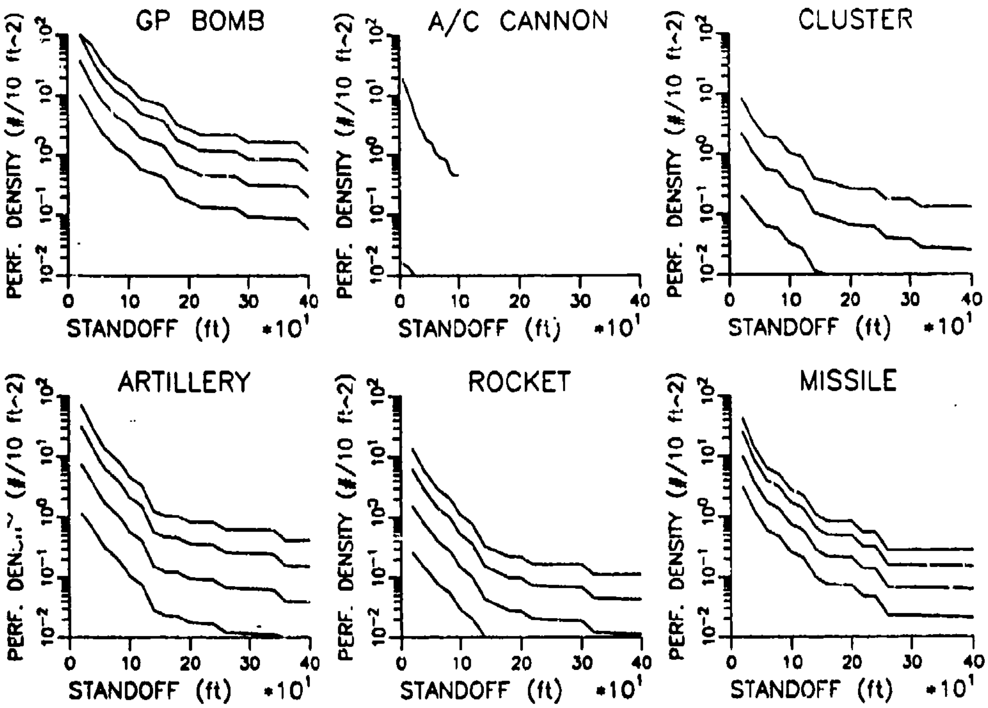


Figure 95. SAFE Fragment Perforation Results for Small Shelter Wall — Soil Bins/Berms.

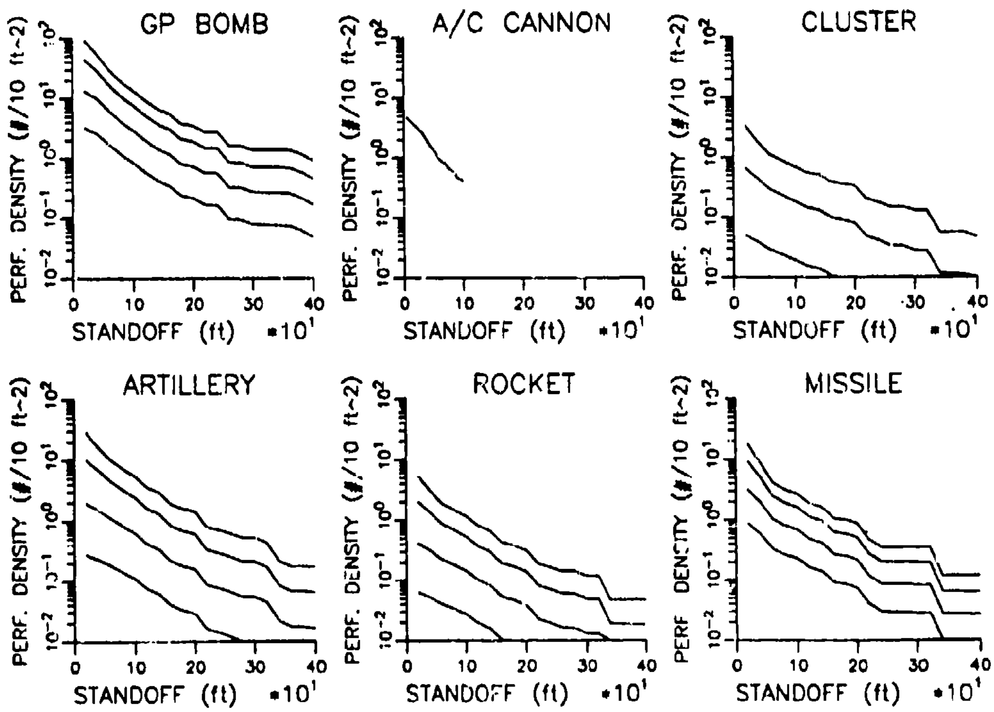
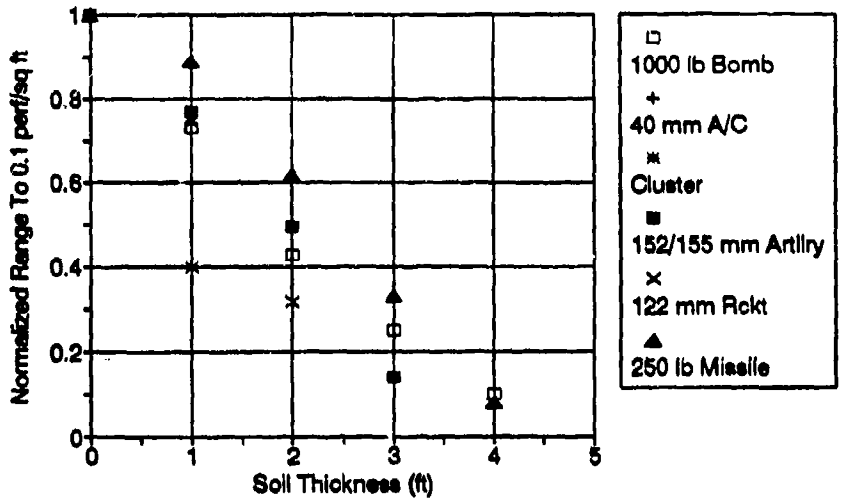
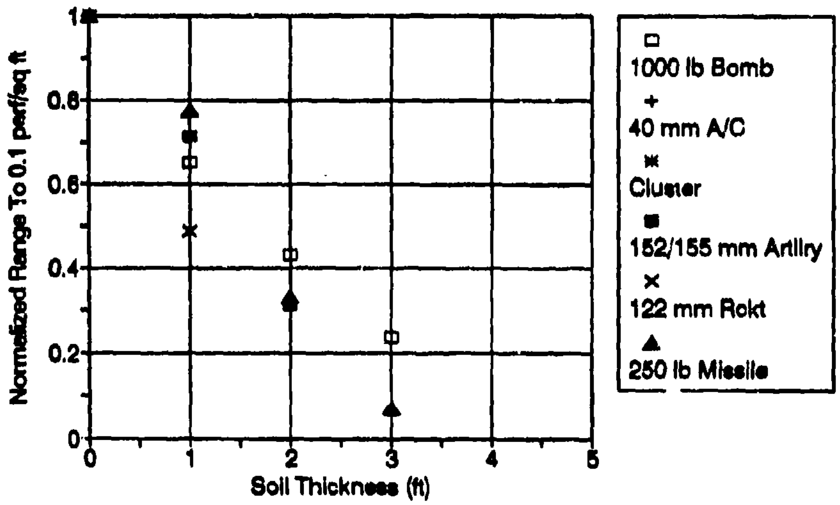


Figure 96. SAFE Fragment Perforation Results for Large Shelter Wall — Soil Bins/Berms.



a. Small Shelter Wall



b. Large Shelter Wall

Figure 97. Normalized Range Reductions for Soil Bins/Berms.

4. Selective Hardening

The SAFE results show that while significant increases in hardness levels can be achieved by incorporating modern ballistic composites such as Kevlar®, Spectra®, and S2-glass, it is not feasible to harden the entire shelter to Splinter levels of protection, as discussed in Appendix H. An alternative to hardening the entire shelter is to selectively harden parts of the shelter. Figure 99 illustrates several selective hardening methods. For example, personnel can be provided ballistic mattresses and/or blankets to cover up with during an attack. Similarly, the

TABLE 29. REQUIRED STANDOFFS FOR 0.1 PERFORATIONS/*FOOT*^{2} — SOIL BINS AND BERMS.

Material Density (*psf*)	Range to 1 Perforation in 10 *Feet*^{2} [a]					
	1000-*lb* Bomb	40-*mm* A/C Cannon	Cluster Munition	152/155-*mm* Artillery	122-*mm* Rocket	250-*lb* Missile
Small Wall						
Unprotected	400	65	100	170	107	147
Soil						
- 12 *inches*	293	-	40	131	80	131
- 24 *inches*	171	-	-	84	34	91
- 36 *inches*	100	-	-	24	-	49
- 48 *inches*	40	-	-	-	-	12
Large Wall						
Unprotected	393	57	70	213	113	180
Soil						
- 12 *inches*	257	-	-	152	55	140
- 24 *inches*	170	-	-	67	-	60
- 36 *inches*	93	-	-	-	-	13
- 48 *inches*	-	-	-	-	-	-

[a] "--" entry means standoff was less than 20 *feet* (5 *feet* for 40-*mm* A/C cannon).

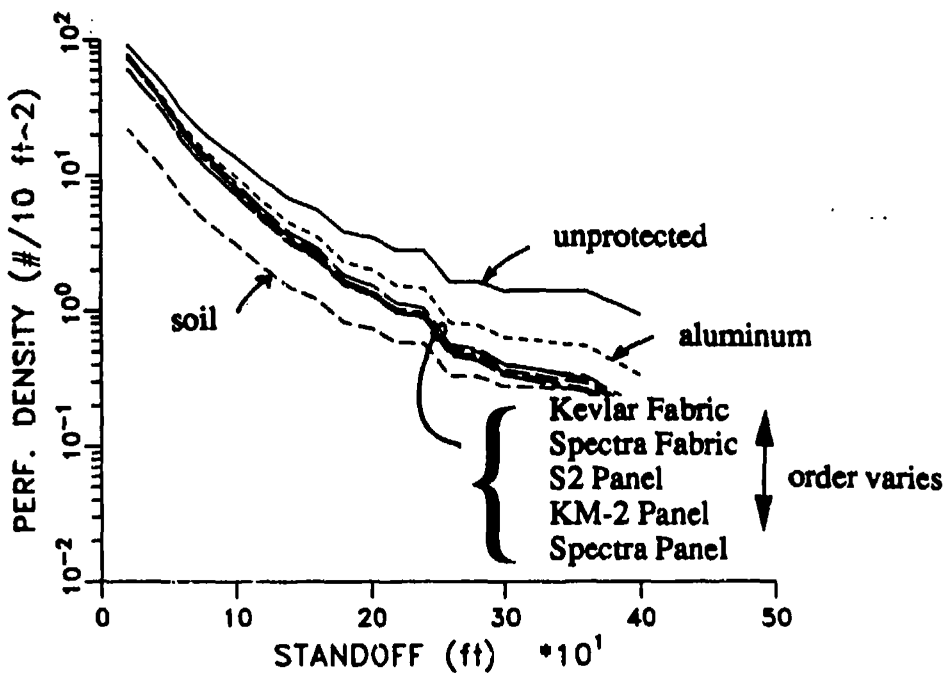


Figure 98. Relative Ballistic Protection Provided by Composite Materials for 1000-*Pound* Bomb.

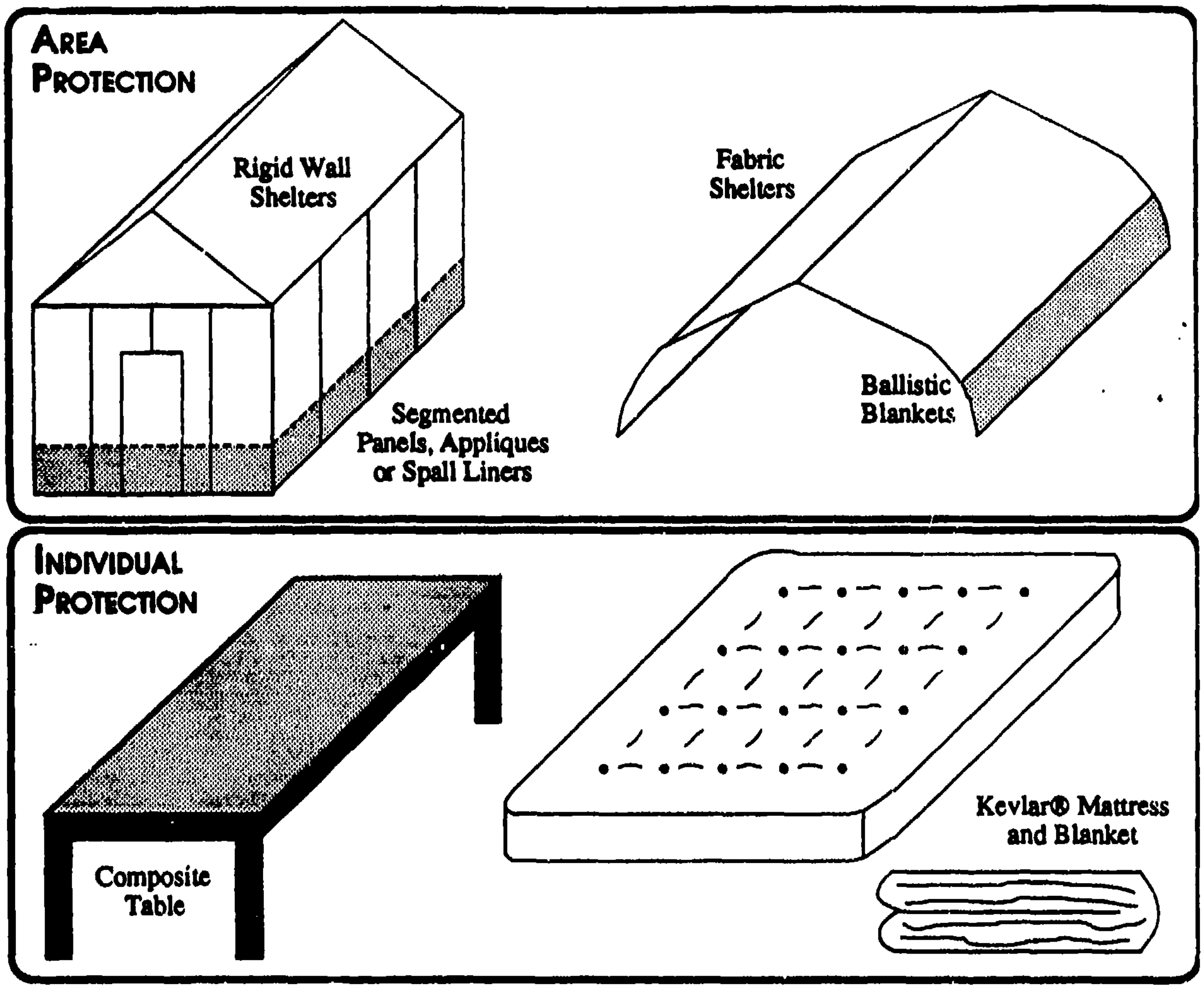


Figure 99. Selective Hardening Concepts.

bottom portion of the shelter walls can be hardened to a very high level to provide a "safe area" for personnel to take cover during an attack. To assess the feasibility of this latter approach, we performed a small number of SAFE analyses in which the ballistic protection was concentrated over the lower 2 *feet* of the small shelter wall instead of being spread out over the entire shelter wall. The remainder of the wall was held constant at an areal density of 1 *psf*. The calculations maintained the same overall panel weight, providing areal densities of 1, 5, 13, and 29 *psf* in the lower 2 *feet* for the four overall wall densities evaluated earlier. Since performance levels for the composite fabrics and panels are very similar, the calculations considered only S2/HJ1 composite panels. We selected S2/HJ1 since the perforation model for this material included data at very high areal densities. We also performed calculations for aluminum panels and soil bin hardening upgrades to provide a basis for comparison.

Figures 100 through 103 and Table 30 present the results of the selective hardening analyses. These results show that selective hardening of the lower 2 *feet* of the shelter wall is an effective means of providing high levels of protection for limited portions of the

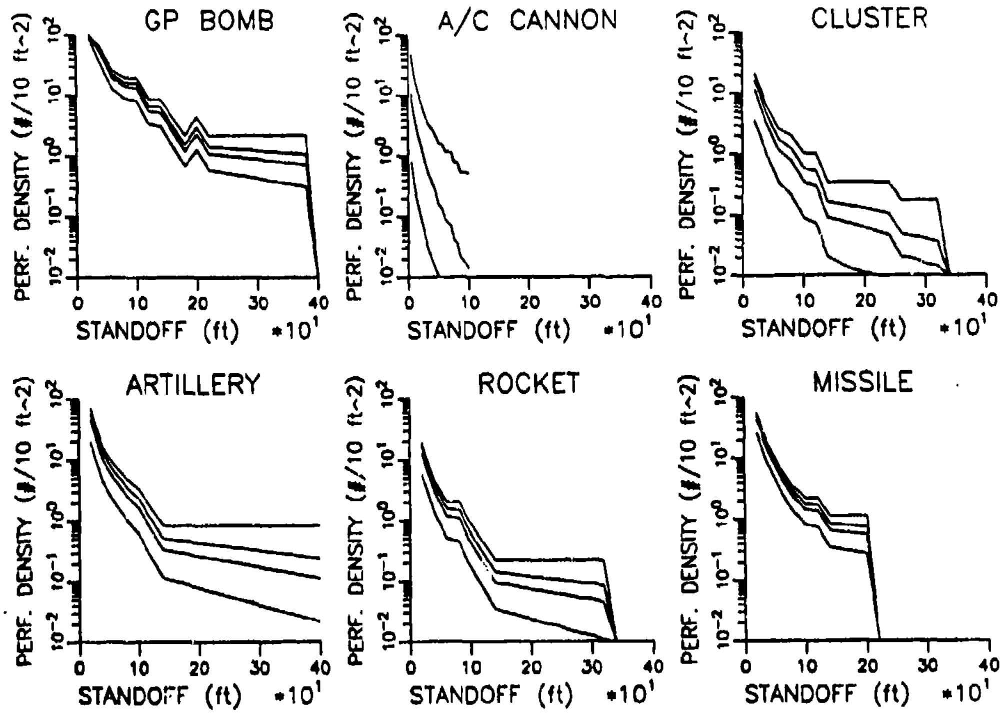


Figure 100. SAFE Perforation Densities for Selectively Hardened Small Shelter Wall — Aluminum Panels.

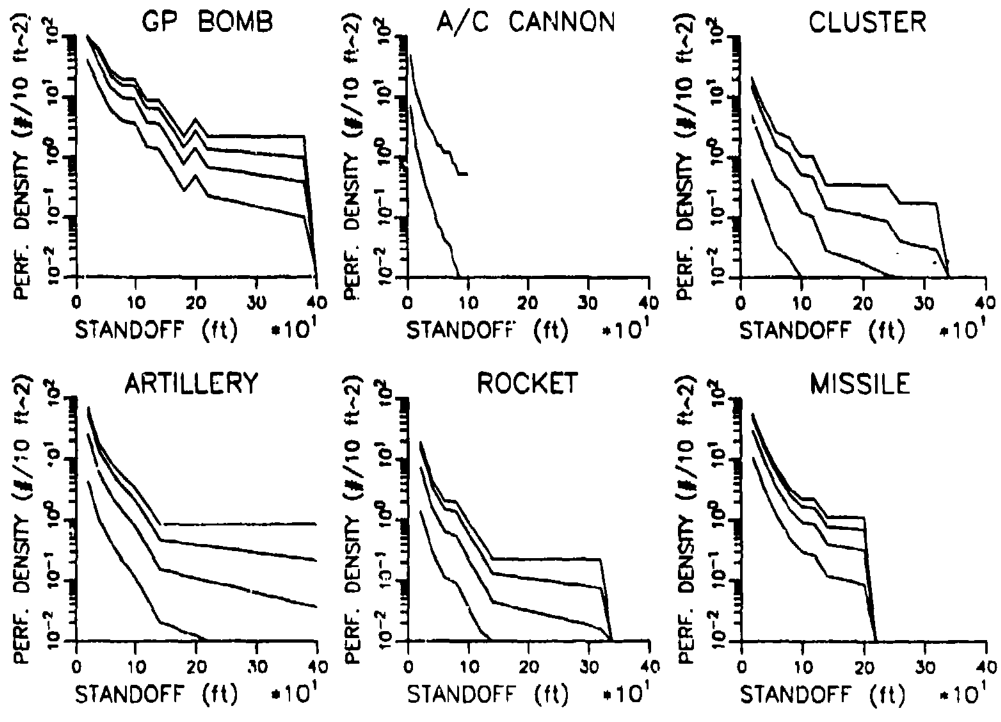


Figure 101. SAFE Perforation Densities for Selectively Hardened Small Shelter Wall — S2/HJ1.

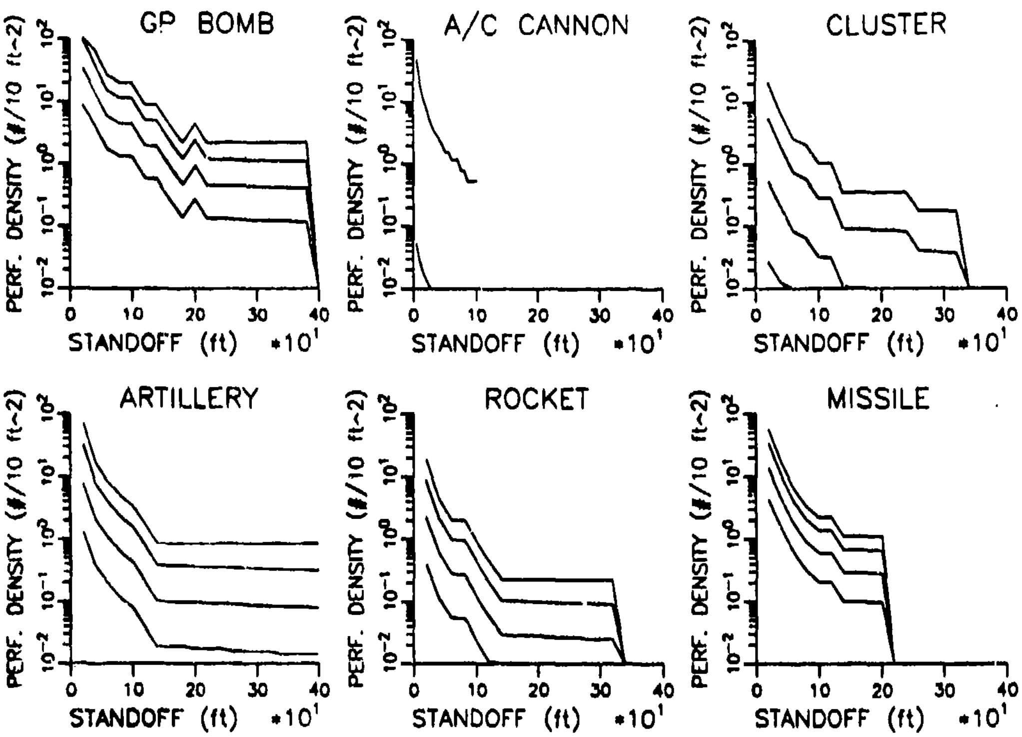
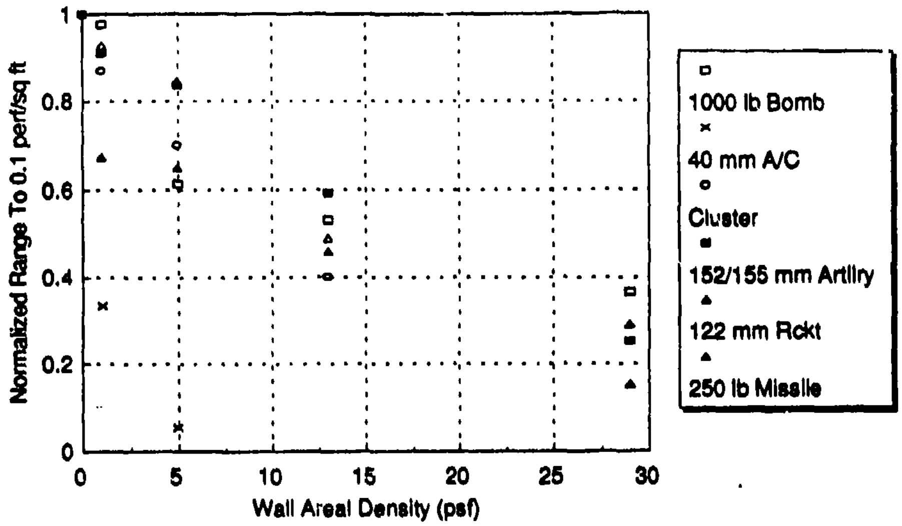


Figure 102. SAFE Perforation Densities for Selectively Hardened Small Shelter Wall — Soil Cover.

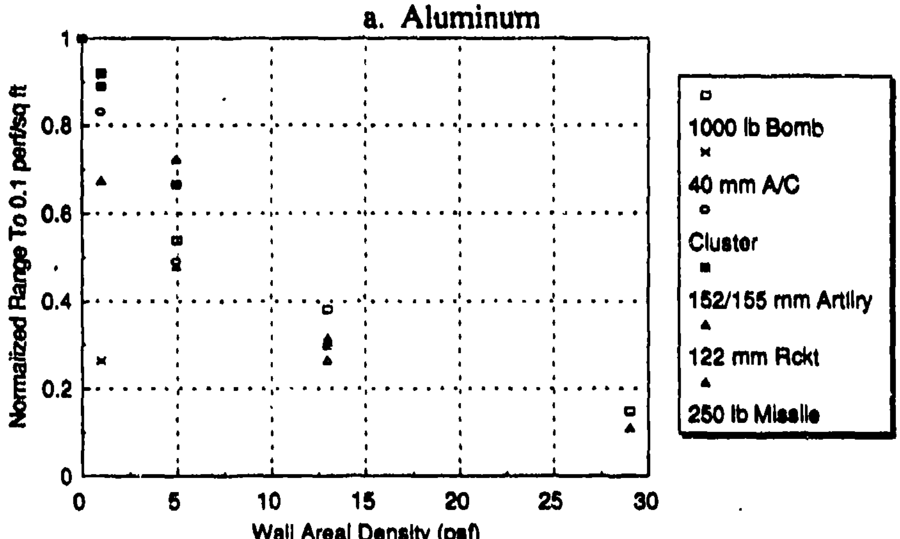
shelter. S2/HJ1 panels with an areal density of 29 *psf* in the lower 2 *feet* (equivalent in total weight to a uniform wall density of 8 *psf* wall) are very effective, reducing required standoffs for 0.1 *perforations/foot*^{2} of selectively hardened area to approximately 20 *feet* or less for all munitions except the 1000-*pound* bomb, which requires a standoff of approximately 60 *feet*. A soil bin with a 4-*foot* thickness is only slightly more effective, reducing the required standoff for the 1000-*pound* bomb to approximately 40 *feet*.

5. Overhead Artillery Threat

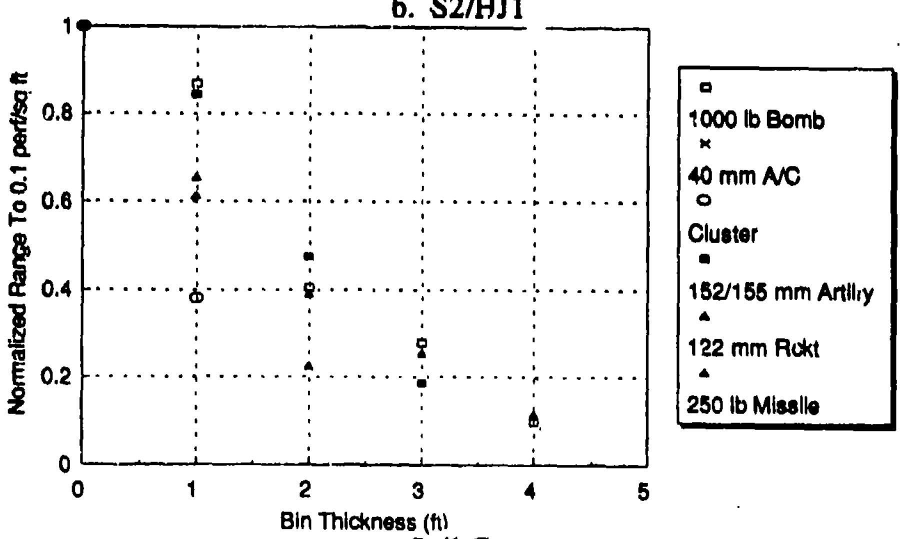
Incoming artillery shells can be proximity fused to provide a height of burst (HOB), spraying fragments over the shelter roof. To address this threat, a limited series of overhead artillery bursts was calculated using the SAFE code. Figure 104 summarizes the problem setup. The calculations assume a small shelter geometry subjected to a matrix of detonation points centered on the long span of the structure with varying HOB (10 to 50 *feet* at 10-*foot* increments) and horizontal standoff (0 *feet*, ±20 *feet*). Three materials are considered: (1) aluminum, (2) S2/HJ1 composite panels, and (3) soil. Since the performance of the ballistic fabrics and composite panels were very similar in previous calculations, a single representative material was selected for the overhead calculations. S2/HJ1 was selected since more data were available for this material and hence, the perforation model was considered more reliable.



a. Aluminum



b. S2/HJ1



c. Soil Cover

Figure 103. Effective Range Reductions for Selective Hardening Upgrades.

TABLE 30. REQUIRED STANDOFFS FOR SELECTIVE HARDENING UPGRADES.

Material Density	Range to 1 Perforation in 10 *Feet*^{2} [a]					
	1000-*lb* Bomb	40-*mm* A/C Cannon	Cluster Munition	152/155-*mm* Artillery	122-*mm* Rocket	250-*lb* Missile
Unprotected Aluminum	391	72	100	135	98	200
- 1 *psf*	382	24	87	123	91	135
- 5 *psf*	240	4	70	113	83	130
- 13 *psf*	208	--	40	80	48	92
- 29 *psf*	143	--	--	34	15	58
S2/HJ1						
- 1 *psf*	360	19	83	120	90	135
- 5 *psf*	211	--	49	92	71	96
- 13 *psf*	149	--	--	40	26	63
- 29 *psf*	58	--	--	--	--	22
Soil						
- 1 *ft*	340	--	38	114	60	131
- 2 *ft*	158	--	--	64	22	78
- 3 *ft*	109	--	--	25	--	51
- 4 *ft*	38	--	--	--	--	23

[a] "--" entry means standoff was less than 20 *feet* (5 *feet* for 40-*mm* A/C cannon).

Figures 105 through 107 present the SAFE results. For each horizontal standoff and material, a family of curves plotting the number of perforations as a function of HOB are provided. The critical cases occur when the artillery shell detonates at a low HOB centered on the shelter roof or when the artillery shell overshoots the shelter (+20-*foot* standoff) and detonates at a HOB between 20 and 40 *feet*, spraying fragments back onto the shelter roof. Figure 108 presents the fragment spray pattern for the latter case with a HOB of 20 *feet* (8 *psf* S2-glass panels). Shown are the cell impact pattern, critical fragment weight, critical fragment velocity, impact angle, and fraction of fragments stopped. Over 99 *percent* of the fragments are stopped over approximately half of the shelter roof; percentages stopped over the other half range from 80 to 99 *percent*. Perforation densities are highest along the edge closest to the detonation. Critical fragment weight along this edge is 50 *grains*, increasing to a 1000 *grains* at the center of the roof. Corresponding velocities range from 5000 *fps* along the edge to 2000 *fps* at the center.

For the materials investigated, soil is the most effective in stopping the fragments from perforation the roof. For 0.1 *perforations/feet*^{2} (64 *perforations*), 24 *inches* of soil performs satisfactorily in most cases. A soil overburden of *36 inches* results in fewer than 0.1 *perforations/feet*^{2} in all cases. S2/HJ1 performs better than Aluminum, with 8 *psf* of material providing fewer than 0.1 *perforations/foot*^{2} at HOBs greater than 30 *feet* (centered) and 50 *feet* (+ 20-*foot* standoff). Extrapolating these results indicates that an areal density on the order of 16 *psf* should provide protection for HOBs greater than 20 *feet* for most standoffs. Aluminum panels are shown not to be effective in providing protection at the areal densities investigated.

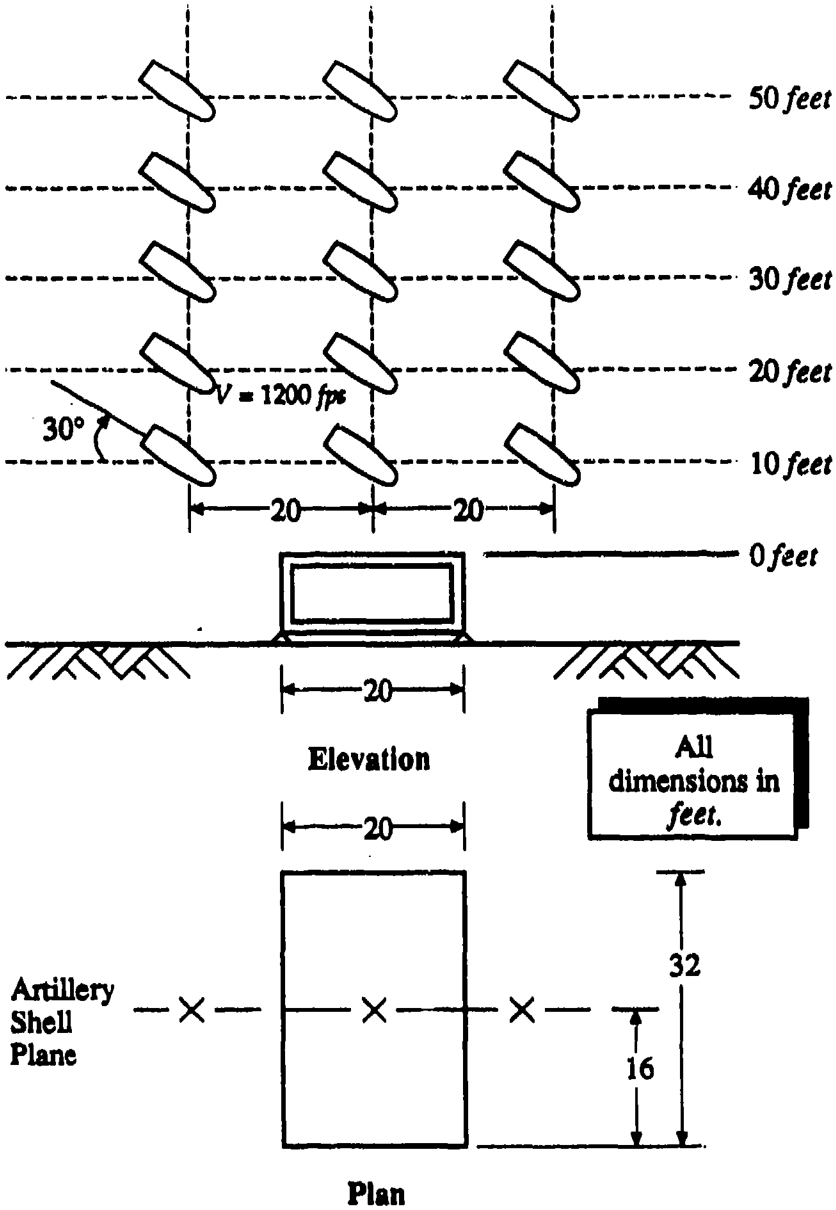
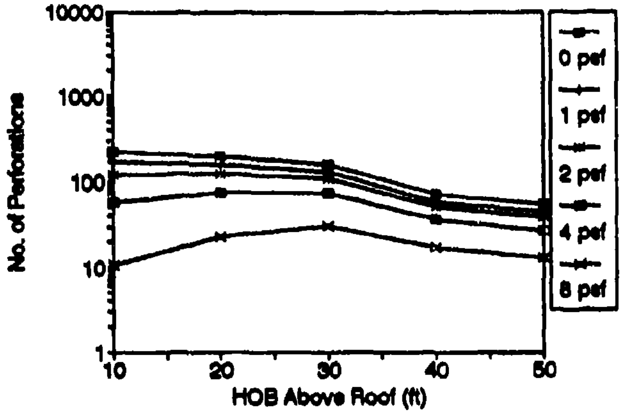
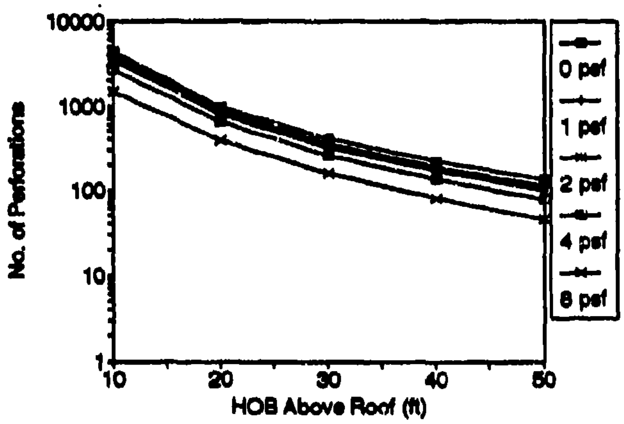


Figure 104. Problem Description for Overhead Artillery Burst.

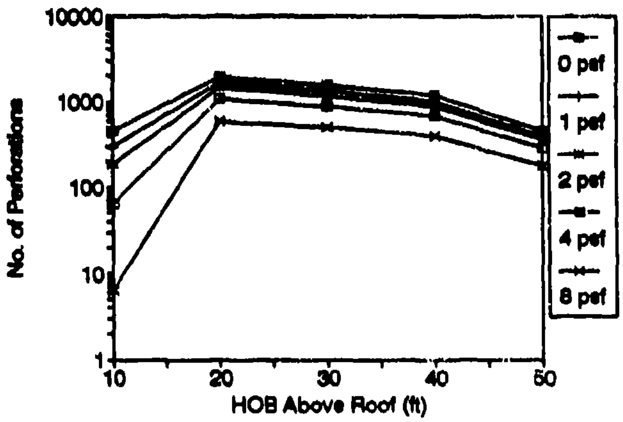
While 2 to 3 *feet* of soil overburden was shown as being effective in providing overhead protection, this depth of overburden creates a severe design implication: the shelter structural system must be designed to support this overburden. These overburden depths translate into gravity loads of 200 to 300 *psf* (assuming a 100 *psf* unit weight for the soil). Only 16 *psf* for ballistic fabrics and advanced composite materials such as Kevlar®, Spectra®, and S2-glass is required. The areal densities for advanced composites are comparable to the design snow loads so that lightweight structures can be designed to support these loads. Hence, a lightly protected or unprotected basic shelter capable of supporting a heavy ballistic fabric/panel upgrade may be an attractive hardening approach for overhead protection.



a. $R = -20\,feet$

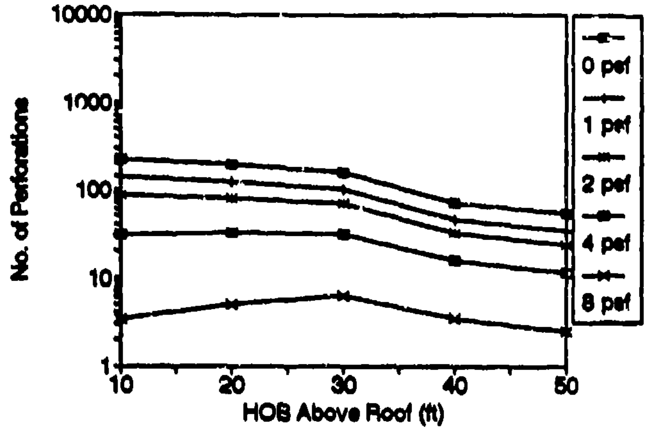


b. $R = 0\,feet$

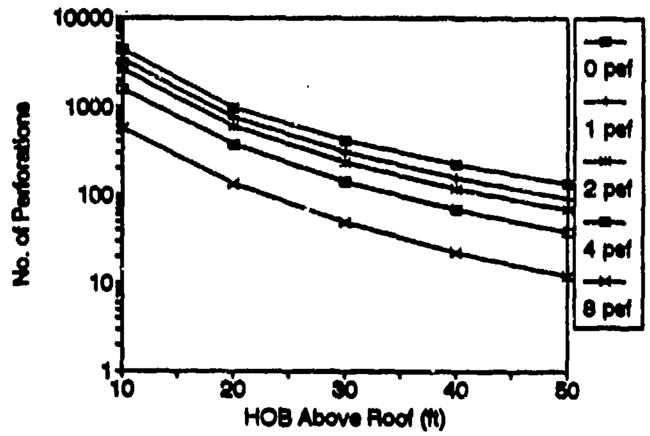


c. $R = +20\,feet$

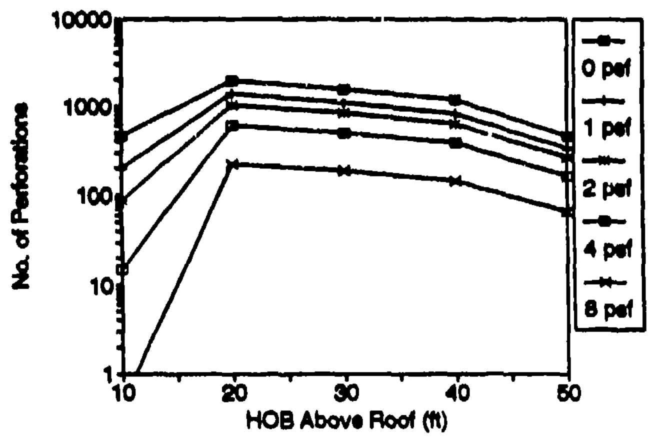
Figure 105. SAFE Overhead Artillery Results — Aluminum Panels.



a. R = - 20 *feet*

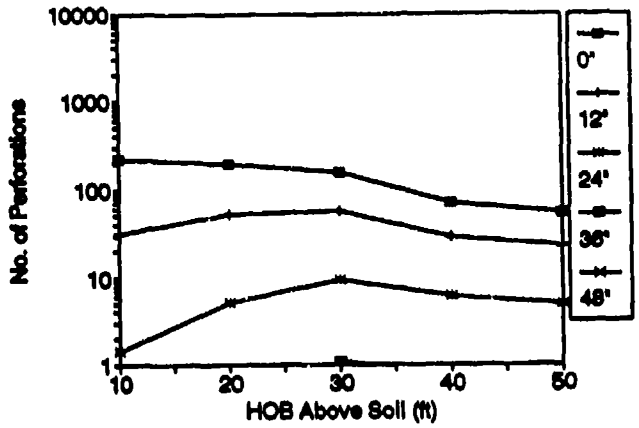


b. R = 0 *feet*

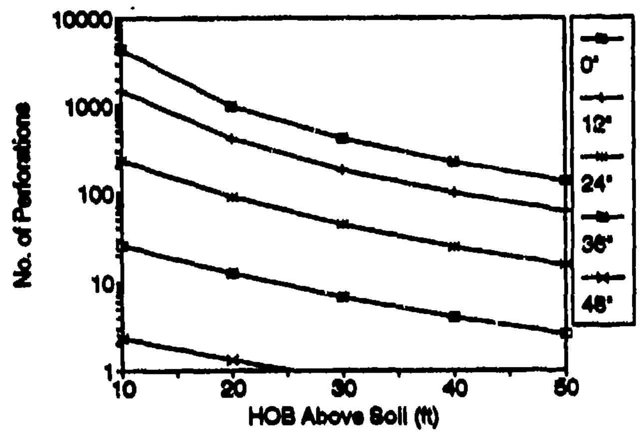


c. R = +20 *feet*

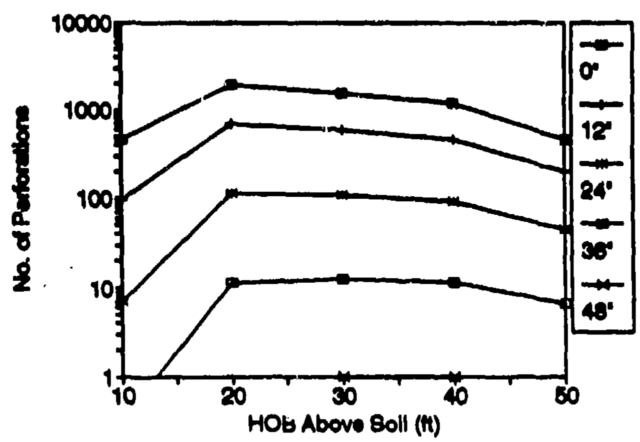
Figure 106. SAFE Overhead Artillery Res its — S2/HJ1 Panels.



a. $R = -20\,feet$

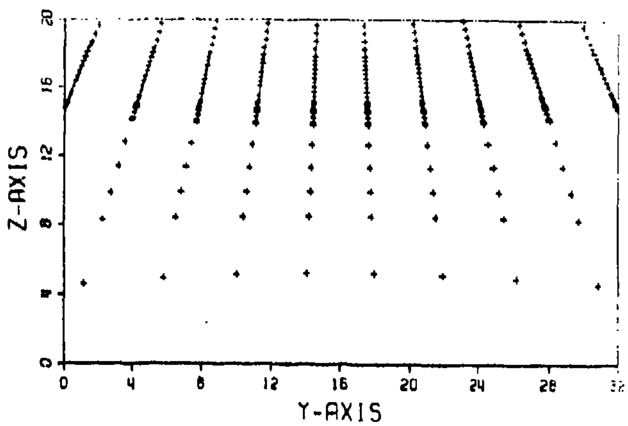


b. $R = 0\,feet$

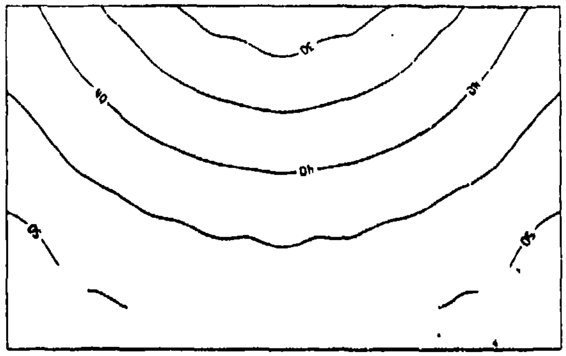


c. $R = +20\,feet$

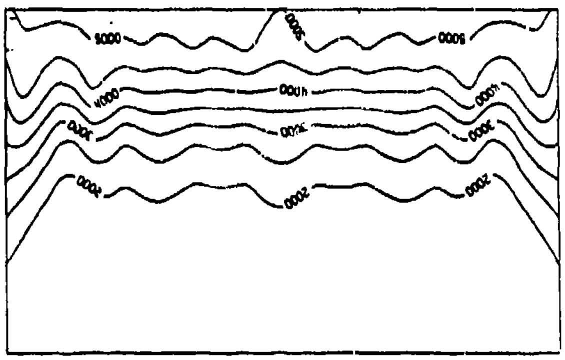
Figure 107. SAFE Overhead Artillery Results — Soil Overburden.



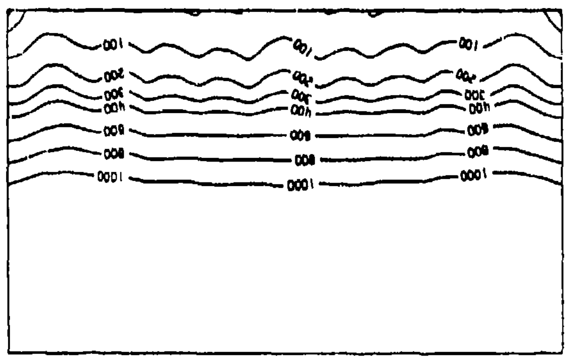
a. Spray Pattern (coordinates in *feet*)



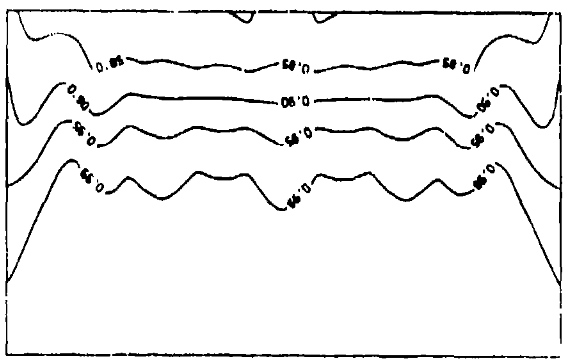
b. Fragment Impact Angle (*degrees*)



c. Critical Fragment Velocity (*fps*)



d. Critical Fragment Weight (*grains*)



e. Fraction of Fragments Stopped

Figure 108. Fragment Impact Contours for Overhead Artillery Burst.

SECTION IV

CONCEPT EVALUATION AND SELECTION

A. INTRODUCTION

In developing and evaluating new shelter concepts, the designer faces several design constraints (*e.g.*, air transportability) that must be satisfied and a wide array of design objectives (*e.g.*, low cost, rapid assembly, low weight, durability, survivability, etc.). Since there are serious conflicts between many of the design objectives, it is not possible to fully satisfy each of the shelter design objectives. Therefore, the selection of the best shelter concept may vary significantly depending on the relative priority or weight assigned to each of the design objectives. Furthermore, since there may be many participants in the decision making process, many different perspectives may have to be considered.

For decision problems involving a limited number of alternatives and objectives, it is usually sufficient to employ informal procedures in selecting the best alternatives. These informal procedures are typically qualitative and are often based on the judgment and experience of the decision maker. For more complex problems, however, it is often beneficial to use formal decision analysis methods to systematically and quantitatively consider trade-offs between design parameters. Formal decision analysis methodologies provide a framework for organizing, assessing, and documenting each of the design constraints, objectives, and alternatives. The number of alternatives and conflicting objectives associated with the portable shelter problem necessitates the use of a formal decision analysis setting.

Formal decision analysis methodologies are comprised of four basic steps as illustrated in Figure 109: (1) structuring the problem alternatives and objectives in a clear, well-defined manner, (2) assessing the probable impact of each alternative using whatever objective and/or subjective information that may be available, (3) determining the preferences of decision makers, and (4) evaluating the alternatives given the information in Steps 1 through 3. Keeney [1982] gives an overview of the elements involved in each of these four steps and the basic axioms associated with them. As Keeney points out, the purpose of decision analysis is to promote insight and creativity in the process of helping decision makers make better decisions. Thus, although we advocate the use of a formal, mathematically-based decision analysis tool, our ultimate goal is to develop common sense engineering criteria and solutions for the next generation of airmobile shelters.

Several decision analysis methodologies have been applied to shelter development problems. Linear weighted objective decision analysis schemes have been used by Schmidt, *et al.* [1988] in a concept study for portable collective protection shelters, by Johnson [1978] in an evaluation of tent concepts, and by Nickerson [1985] in a concept study for chemically hardened battalion aid stations. Steeves [1987] uses Saaty's analytical hierarchy process to evaluate tent concepts for use in a chemical warfare environment. Seabold, *et al.* [1986] have implemented a

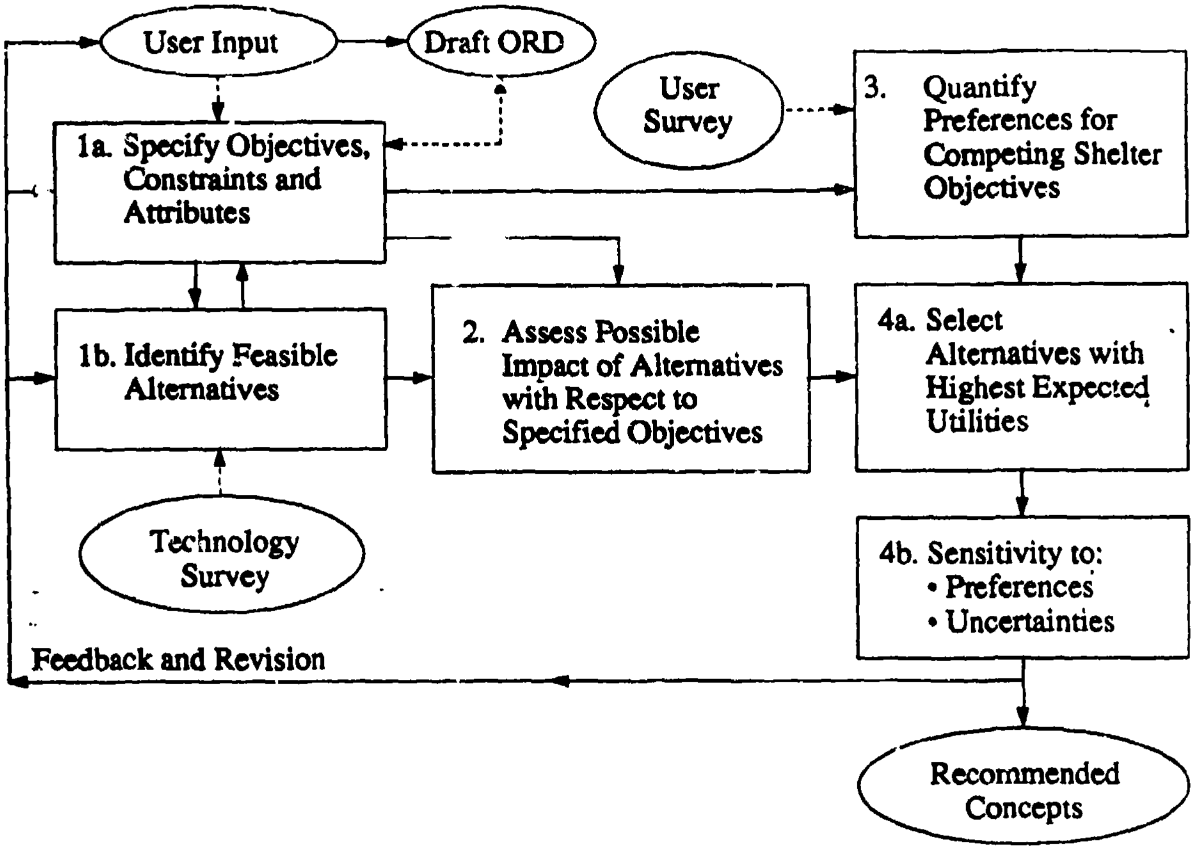


Figure 109. Concept Evaluation Methodology.

cost/benefit/time utility model for shelter selection. Other decision analysis tools (*e.g.*, linear programming, dynamic programming, etc.) are also available.

The decision analysis methodology that we believe is best suited for the shelter selection problem is multi-attribute utility theory [Raiffa, 1969; Fishburn, 1970; and Keeney and Raiffa, 1976]. Figure 110 is a schematic diagram of inputs and outputs for the Airmobile Shelter Evaluation Methodology (ASEM) implemented in Sections C through F.[1] This figure is provided for reference throughout Section IV. Before proceeding to the ASEM model description, we briefly review the fundamentals of utility theory and multi-attribute decision analysis to introduce concepts and terms used in the description of the ASEM model and in the summary of the shelter evaluation results.

B. MULTI-ATTRIBUTE DECISION ANALYSIS

In this section, we briefly define some of basic terms used in utility theory and multi-attribute decision analysis. The purpose of utility theory is to provide a framework in which

[1]Additional details on the ASEM code organization and implementation are provided in Appendix D.

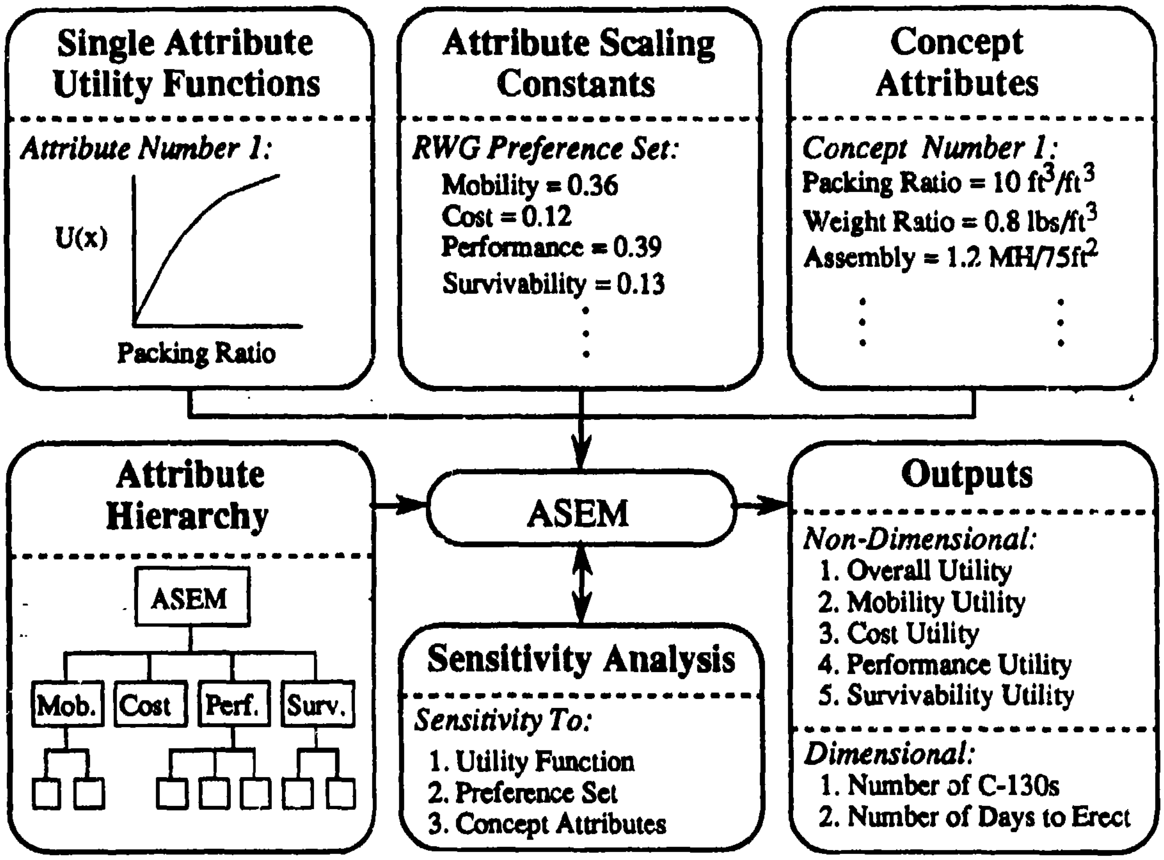


Figure 110. ASEM Inputs and Outputs.

design attributes can be measured, combined, and compared consistently with respect to a decision maker's values and preferences [Ang and Tang, 1984]. The multiattribute decision analysis tool developed for this study draws heavily on the concepts of utility theory.

An *attribute* is a parameter that can be used to measure the degree to which a specific objective is achieved. For example, low initial cost is an objective that can be measured in terms of dollars, and lightweight is an objective that can be measured in pounds. Another important term is *utility*, sometimes also referred as *value* or *intrinsic worth*. Based on a scale of 0 to 1, utility quantifies the intrinsic worth of a particular value of an attribute to the decision maker (DM). The *certainty equivalent* (CE) of an attribute is the value of the attribute at which the DM is indifferent between that value and a 50-50 chance at either the best value of the attribute or the worst value of that attribute. Finally, a *threshold* or *constraint* is the minimum acceptable value of achievement for an attribute, and an attribute *goal* is a desired level of performance.

As the number of attributes to be considered increases and the preference set of the DM becomes more complex, a well-defined hierarchical structure for the decision problem is required. The sequence of steps required to build and analyze the hierarchy and to evaluate the marginal and combined utility functions is described in the following subsections.

1. Creating the Hierarchical Structure

Hierarchies provide a structure for modeling individual objectives and their relationships to one another. Obviously, the objectives must be specific enough to successfully differentiate between competing alternatives. The hierarchical structure is a tool for constructing and documenting a complete list of relevant objectives and attributes. Through the hierarchy, the overall objectives of the decision analysis problem are decomposed into manageable and distinct parts. Starting at the highest level objectives, we proceed downward until we reach the bottom-level objectives to which meaningful measures of achievement (*i.e.*, attributes) can be attached. In some cases, qualitative attributes may be required (*e.g.*, to describe the level of shelter modularity). The collection of sub-objectives at each level in the hierarchy forms a submodel. After scaling and combining these submodels in a manner that reflects the preferences of the DM, the attributes of the bottom level objectives are translated into an overall measure of success.

2. Joint Utility Function Simplifications

(a) Preferential Independence

Suppose that there are three or more attributes describing the objectives at a given level in the hierarchy. If the DM's preference between x_1 and x_2 is unaffected by the values of attributes $x_3, x_4, \ldots, x_n$, then x_1 and x_2 are said to be Preferentially Independent (PI). If PI is not initially satisfied, it may be possible to achieve PI through a reorganization of the hierarchic structure. For example, if x_3 influences the DM's preferences between x_1 and x_2, then this may imply that the objective corresponding to x_3 should be placed above or below the objectives associated with x_1 and x_2 in the hierarchy instead of parallel to them. In cases where the hierarchy cannot be reorganized to create PI, a common approach is to proceed with the assumption of PI and then check the sensitivity of the results to the PI assumption.

(b) Utility Independence.

Utility Independence (UI) is said to hold if the utility of an attribute remains the same regardless of changes in the values of the other attributes at that level. In case of a violation of UI, one can infer that the utility of a particular attribute is affected by some other attribute(s) at the same level. Hence, as discussed for preferential independence, modifications of the hierarchical structure may be beneficial if UI does not hold.

3. Assessing Single Attribute Utilities.

The utility function of each continuous attribute is assumed to be of exponential form and is fit based on the lowest, highest and median values of the attribute. Although other common types of utility functions are available (*e.g.*, logarithmic or quadratic), Ang and Tang [1984] have shown that the overall utility of an alternative is relatively insensitive to the form of the utility function. The general form of an exponential utility function is

$$U(x) = a - b \exp(-rx) \tag{15}$$

where r is called the "index of absolute risk aversion" and is defined as

$$r = -\frac{U''(x)}{U'(x)} \tag{16}$$

where primes denote derivatives of the utility function with respect to x. The exponential utility function is characterized by a constant level of risk aversion (*i.e.*, r is independent of x). Risk aversion implies that the marginal increases in utility decrease with increasing values of the attribute. A risk averse DM is conservative in that he/she always prefers the expected outcome of a lottery to a chance at achieving the more preferable consequence of the lottery. The negative sign in the exponent of Equation (15) ensures that r is positive for a risk-averse DM.

If we define x^0 as the value of the attribute that produces the lowest utility and x^* as the value that produces the highest utility (*i.e.*, $U(x^0) = 0.0$ and $U(x^*) = 1.0$), then the constants a, b, and r can be computed by solving three simultaneous equations:

$$1 = a - b\,exp(-rx^*) \tag{17a}$$
$$0 = a - b\,exp(-rx^0) \tag{17b}$$
$$U(x) = a - b \exp(-rx) \tag{17c}$$

Typically, the value of x in Equation (17c) is taken to be the median value (*i.e.*, the CE value or the value of x associated with a utility of 0.5).

For discrete attributes, utility functions are treated as a series of step functions which are defined at a finite number of points. The utility values at each level in the step function are fixed based on the preferences of the DM.

4. Ordering the Scaling Constants.

The preferential order of all the attributes at each level must be determined. All the attributes at a certain level are given their worst possible values to start with. The DM is then asked which one of these he/she would like to increase to the best level. This attribute will have the largest value of the scaling constant. This process is repeated until an order for all the attributes is established.

5. Evaluating the Scaling Constants.

The relative preferences of the DM for achieving different design objectives are characterized by a set of attribute scaling constants. Under additive independence (see Section B.6), the scaling constants can be interpreted as the relative importance associated with increasing each attribute from its worst level to its best level (*i.e.*, from x_i^0 to x_i^*). There are two methods for computing scaling constants: the direct approach and the indirect approach.

(a) **Direct Approach**

A single attribute at a given level in the hierarchy is selected, say x_1, and the following lottery is constructed:

Choice I. x_1 at its best possible value and all the other attributes at their worst possible value. This set of attributes is denoted as $\{x_1^*, x_2^0, \ldots, x_n^0\}$.

Choice II. There is a probability p that all the attributes at that level are at their best possible values (*i.e.*, $x_i = x_i^*$ for all i) and a probability $1 - p$ that all the attributes are at their worst values (*i.e.*, $x_i = x_i^0$ for all i).

The lottery is written symbolically as

$$\{x_1^*, x_2^0, \ldots, x_n^0\} \sim \langle \{x_1^*, x_2^*, \ldots, x_n^*\}, \{x_1^0, x_2^0, \ldots, x_n^0\}; p \rangle \tag{18}$$

where Choice I is on the left, Choice II is on the right, and ~ denotes indifference. Note that the DM is being asked to choose between a certain event (Choice I) and an option that has an uncertain outcome (Choice II). The value of p that makes the DM indifferent between these two choices is the scaling constant for the attribute x_1.

(b) **Indirect Approach**

Consider the pair of attributes at a given level with the highest scaling constants, say x_1 and x_2, and assume that x_1 is preferred to x_2. Now we construct the following two choices:

Choice I: The attribute x_1 is given at its best value and x_2 is given at its worst value (*i.e.*, $x_1 = x_1^*$ and $x_2 = x_2^0$).

Choice II: The attribute x_1 at some value x_1' (to be evaluated) and the attribute x_2 is given at its best value (*i.e.*, $x_1' = x$ and $x_2 = x_2^*$).

The choices are written symbolically as

$$\{x_1^*, x_2^0\} \sim \{x_1', x_2^*\} \tag{19}$$

The value x_1' is the value of attribute x_1 that makes the DM indifferent between the two choices. If k_1 and k_2 are the scaling constants of attributes x_1 and x_2 respectively, then

$$k_2 = k_1 * u_1(x_1') \tag{20}$$

where $u_1(x_1')$ is the utility of the attribute x_1 when it takes the value x_1' [Keeney and Raiffa, 1976]. Taking other pairs, one can generate n - 1 independent equations (n = number of attributes at the current level) of this type. Using the direct approach to compute the scaling constant of one of the attributes at this level, the remaining scaling constants can be calculated using the indirect approach.

6. Choosing a Form for the Joint Utility Functions.

Under the independence assumptions discussed in Section IV.B.2 (*i.e.*, mutual preferential independence and mutual utility independence), the form of the joint utility function at a given level must be either additive or multiplicative [Keeney and Raiffa, 1976]. Additivity is a simpler but more restrictive form of independence than multiplicative independence. Three checks are available for determining whether additivity is appropriate:

Check 1: ***Sum of k_i's.***

- Determine the set of scaling constants using the procedure outlined in *Section IV.B.5.b*.
- If the sum of the scaling constants is equal to or approximately equal to one, then additivity holds.

Check 2: ***Setting Up Test Lottery Alternatives.***

- Choose a pair of attributes (*e.g.*, the two with the highest scaling constants).
- Check the order of preference for the following lotteries :

$$\langle\{x_i^*, x_j^*\}, \{x_i^0, x_j^0\}; 0.5\rangle \text{ vs. } \langle\{x_i^*, x_j^0\}, \{x_i^0, x_j^*\}; 0.5\rangle \tag{21}$$

- If these are of equal preference (or approximately so), then this is consistent with additive independence. Repeat this check for additional pairs of attributes, as necessary.

Check 3: ***Consistency Check.***

- Select two attributes, say x_1 and x_2, and find the indifference probability for the following choice:

$$\{x_1^*, x_2^*, x_3^0, \ldots, x_n^0\} \sim \langle\{x_1^*, x_2^*, x_3^*, \ldots, x_n^*\}, \{x_1^0, x_2^0, x_3^0, \ldots, x_n^0\}; r\rangle \tag{22}$$

- Consistency with additivity (together with mutual utility independence) demands that $r = k_1 + k_2$.

If, on the basis of one or more of the above checks, the attributes are shown to be additive, the joint utility function for that level of the hierarchy is simply

$$u(x_1, \ldots, x_n) = \sum_{i=1}^{n} k_i\, u_i(x_i) \tag{23}$$

If additivity does not hold, but preferential independence and utility independence do hold, the joint utility function must be multiplicative. In the multiplicative case, the overall utility is calculated by solving

$$1 + ku(x) = \prod_{i=1}^{n} [1 + k\, k_i\, u_i(x_i)] \qquad (24)$$

for $u(x)$. The parameter k, called the interaction constant, is evaluated by the following system of equations:

$$1 + k = \prod_{i=1}^{n} (1 + k\, k_i) \qquad (25)$$

Working up from the bottom level objectives, the joint utility function at each level is calculated using the procedures described above. We continue until the top level of the hierarchy is reached, resulting in an expression for the overall utility function.

C. AIRMOBILE SHELTER DECISION ANALYSIS HIERARCHY

1. Objectives

Before proceeding to the detailed hierarchy of shelter attributes, we briefly recapitulate the four major, first-level shelter objectives: (1) high mobility, (2) low cost, (3) good fundamental sheltering capabilities, and (4) protection from weapon effects. These four objectives provide the basic framework for the hierarchy of shelter attributes that is presented in the next subsection.

Mobility. Shelter mobility encompasses two major sub-objectives: transportability and rapid assembly. Mobility is expected to be the prime concern of those involved in airlifting and erecting/striking the new FOPS. Although we have chosen to group transportability and rapid assembly under the combined objective of mobility, the subobjectives can be severely conflicting in some cases. Nonexpandable tactical shelters offer an extreme example of this conflict. Because they are essentially ready-to-use shelters, nonexpandables tend to have rapid erection rates and generate high airlift demands.

Cost. Three basic elements of shelter cost are considered in the Airmobile Shelter Evaluation Methodology (ASEM) model: initial unit cost, redeployment costs, and expected lifetime of the shelter. Thus, the cost objective is to minimize expected life cycle costs. We must emphasize, however, that a formal life cycle analysis (*i.e.*, discounting of future costs, *etc.*) is not performed in ASEM. The level of design detail at this stage of concept development is not sufficient for such an analysis.

Basic Shelter Performance. The attributes of a shelter concept that contribute to its ability to provide a habitable, productive living/work space and basic protection from environmental loads are combined under the first-level objective of basic shelter performance. As the development of the new FOPS progresses and the shelter designs become more detailed, the shelters will be required to meet specific DOD human factors criteria, structural reliability criteria, *etc.* The basic shelter performance objective serves as a placeholder for these future design requirements.

Survivability. Protecting shelter occupants and contents against weapon threats is a key requirement for the new FOPS. Therefore, survivability has been specified as one of the four first-level objectives. Within this objective, there are two major categories of weapon threats to be considered: (1) small arms threats and fragment/airblast producing weapon threats, and (2) chemical and biological (CB) weapon threats. Although CB weapons represent a major threat to portable shelters, these threats are not currently included in the ASEM hierarchy. As Section III indicates, the primary purpose of this study is to determine the feasibility of hardening portable shelters against fragmentation and small arms effects through the application of hardening upgrades to the basic shelter design concepts. CB protection is generally achieved through careful design of both the shelter cladding system and the shelter HVAC system. This level of design detail is beyond the scope of the present study. In addition, considerable research and development effort has already been expended on the question of CB protection. Therefore, the focus for this study has been on the non-CB survivability criteria specified in the FOPS ORD.

2. Attributes and Constraints

The attributes used in ASEM to assess the candidate small and large shelter concepts are summarized in this subsection. The attributes are arranged in a hierarchy consisting of four major branches that directly correspond to the four major shelter design objectives: mobility, cost, performance, and survivability. Each of the major branches includes one or more levels of lower level attributes.

As of June 1992, the portable shelter ORD Requirements Correlation Matrix (RCM) specified six major categories of shelter characteristics. Two of the major ORD RCM categories, transportability and rapid assembly, have been placed under the ASEM first-level attribute mobility. Similarly, the ORD RCM categories reliability/maintainability and functionality/operability have been placed under the ASEM first-level attribute performance. The remaining two ORD RCM categories, hardness and cost, directly correspond to the other two ASEM first-level attributes, survivability and cost, respectively.

Only the lowest level attributes in each branch of the hierarchy are input into ASEM. Therefore, detailed descriptions of each of the lowest level attributes are provided in this subsection to completely define the ASEM attribute inputs for both small and large shelters. Within the ASEM code, the lowest level attributes are combined to measure the degree to which a concept meets the four major objectives as well as other high level measures of overall concept desirability. The procedures for combining or scaling the low-level attributes and for formulating the high level performance measures are discussed in Appendix D. The scaling constants used in the shelter evaluation studies are summarized in Section C.3.

The hierarchy of shelter attributes used in ASEM is illustrated in Figure 111. To simplify references to the ASEM attributes, the attributes are numbered according to their positions within the overall hierarchy. The first-level attributes are denoted by a single upper

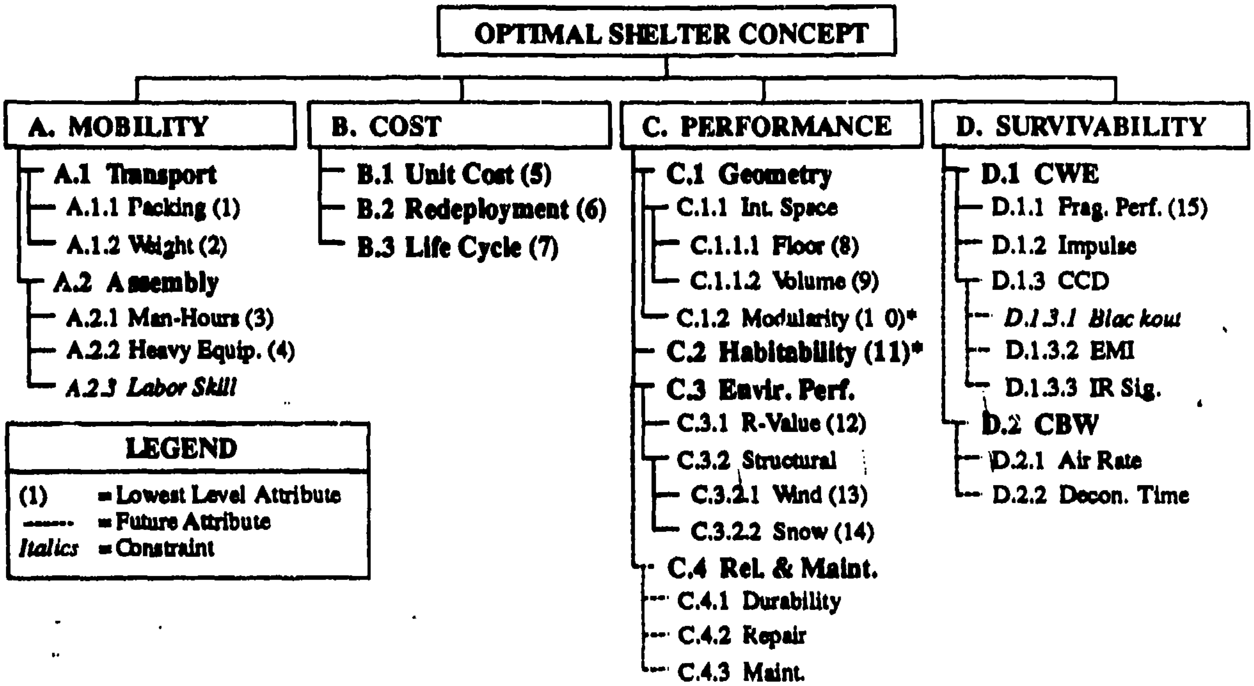


Figure 111. Airmobile Shelter Design Analysis Hierarchy.

case letter (*i.e.*, A, B, C, and D). Attributes at the next level are denoted by a letter and one number (*e.g.*, A.1, A.2), and attributes at subsequent levels are denoted by an additional number for each additional level of depth (*e.g.*, A.1.1, A.1.2).

The small and large shelter lowest-level attributes and constraints are defined in the following paragraphs and summarized in Table 31. Figure 112 shows plots of the 13 continuous single attribute utility functions. Best, worst, and median values are specified for each lowest-level attribute. The best and worst values correspond to the attribute utilities of 1.0 and 0.0, respectively. These values are based on the data summarized in Sections II and III. The median value represents our estimate of the point at which a typical decision maker would be indifferent between a 50-50 chance of getting the lowest or highest value versus a sure bet (*i.e.*, 100 *percent* chance) of getting the median value. Ideally, the median values should be specified by a consensus of AF decision makers. Since it was not possible to develop such a consensus within the scope of this effort, we developed best-estimate median values based on our interactions with AF personnel. Whenever guidance has been specified in the ORD RCM, these values are also reported for the lowest level attributes. ORD specifications are either in the form of thresholds (*i.e.*, minimum acceptable performance levels) or in the form of objectives (*i.e.*, levels of performance that represent significantly improved performance over the corresponding threshold).

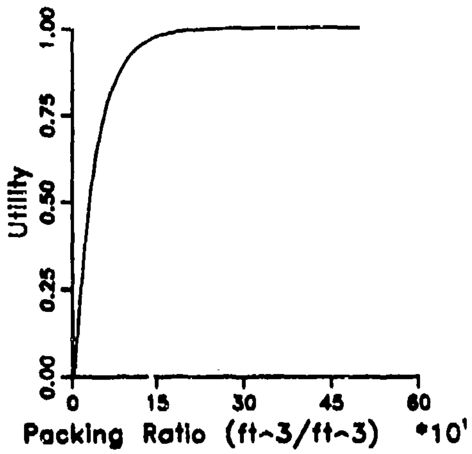
A.1.1 ***Packing Ratio.*** The ratio of the usable shelter volume to the packed volume of the shelter.

TABLE 31. SUMMARY OF SHELTER ATTRIBUTES AND CONSTRAINTS.

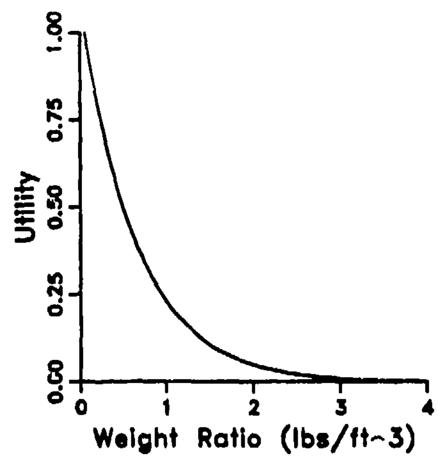
Position	Attribute	Units	ASEM			ORD	
			Worst	Median	Best	Threshold	Objective
A	**Mobility**						
A.1	***Transportability***						
A.1.1	Packing Ratio	*feet³/feet³*	3	30	500	--	--
A.1.2	Weight Ratio	*pounds/feet³*	4	0.5	0.05	--	--
A.1.3	463L Compatibility	--		Constraint			
A.2	***Rapid Assembly***						
A.2.1	Man-Hours	*MH/75 feet²*	12	0.8	0.2	1.0	0.75
A.2.2	Heavy Equipment	EH/600 *feet²*	10	1	0	--	--
A.2.3	Labor Skills	--		Constraint		--	--
B	**Cost**						
B.1	***Unit Cost***	*$/feet²*	600	100	1	--	--
B.2	***Redeployment Costs***	*Percent*	100	20	0	--	--
B.3	***Life Cycle***	# Deploy	1	12	30	12	20/26
C	**Shelter Performance**						
C.1	***Geometry***						
C.1.1	Interior Space						
C.1.1.1	Floor Space Ratio	*feet²/feet²*	0.5	1.0	2.0	--	--
C.1.1.2	Volume Ratio	*feet³/feet³*	0.5	1.0	2.0	--	--
C.1.2	Ext. & Modularity	*Points*		See Text		--	Yes
C.2	***Habitability***	*Points*		See Text		Exp. Floors	Rigid Floors, Doors
C.3	***Environmental Perf.***						
C.3.1	R-Value	*Hour foot² °F/Btu*	0.5	3	20	--	--
C.3.2	Structural Loads						
C.3.2.1	Sustained Wind	*mph*	20	60	100	80	--
C.3.2.2	Snow Load	*psf*	5	20	40	10	--
C.4	***R & M***						
C.4.1	Durability	*hours*		For Future Use		--	--
C.4.2	Repairability	*MH*		For Future Use		--	--
C.4.3	Maintainability	*MH*		For Future Use		--	--
D	**Survivability**						
D.1	***CWE Survivability***						
D.1.1	Fragment Perforations	#/10 *feet²*	1.0	0.2	0.0	Splinter	Semi-Hardened
D.1.2	Impulse	*psi-ms*		For Future Use		--	--
D.1.3	CCD						
D.1.3.1	Blackout	--		Constraint		--	Yes
D.1.3.2	EMI	--		For Future Use		--	Yes
D.1.3.3	Infrared Signature	--		For Future Use		--	Yes
D.2	***CBW Survivability***						
D.2.1	Air Leakage Rate	*feet³/min*		For Future Use		--	--
D.2.2	Decon. Time	*MH/100 feet²*		For Future Use		--	--

Worst value = 3:1
Best value = 500:1
Median value = 30:1
ORD threshold = none
ORD objective = none

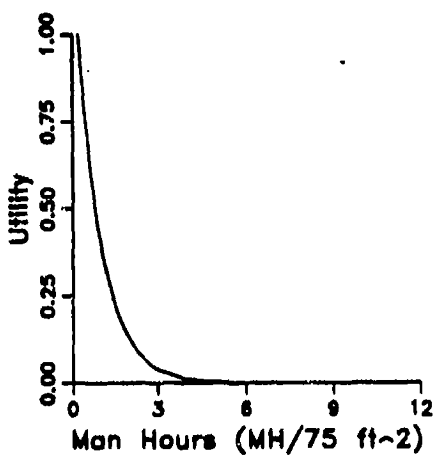
A.1.2 ***Weight Ratio.*** The total weight of the shelter divided by its usable volume.



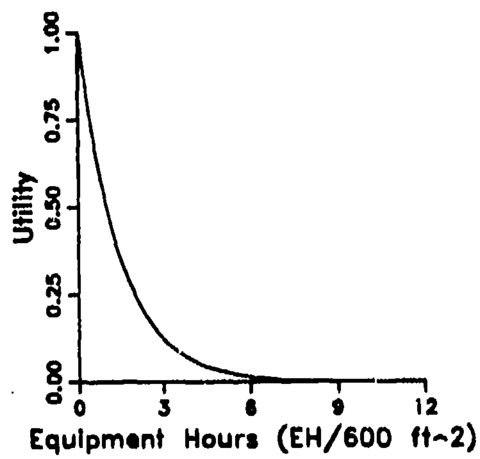
a. Attribute A.1.1



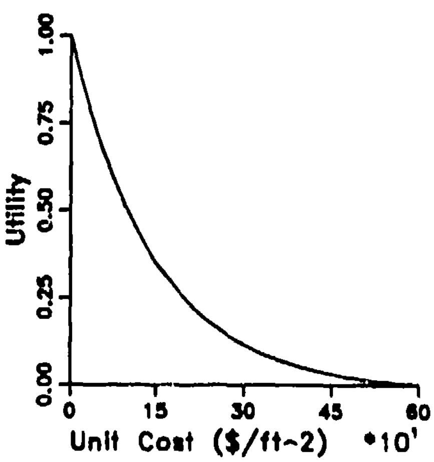
b. Attribute A.1.2



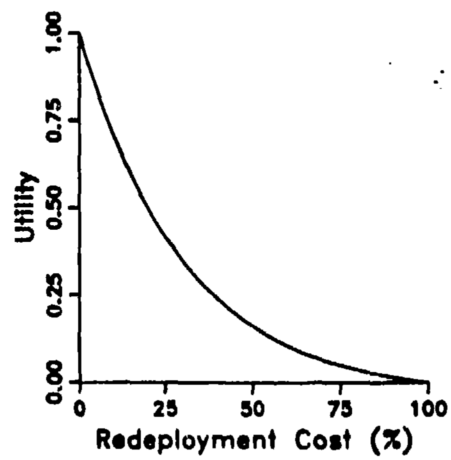
c. Attribute A.2.1



d. Attribute A.2.2

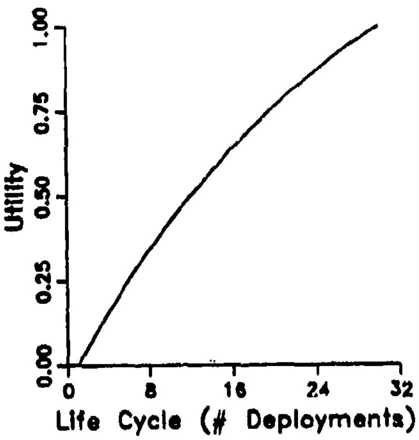


e. Attribute B.1

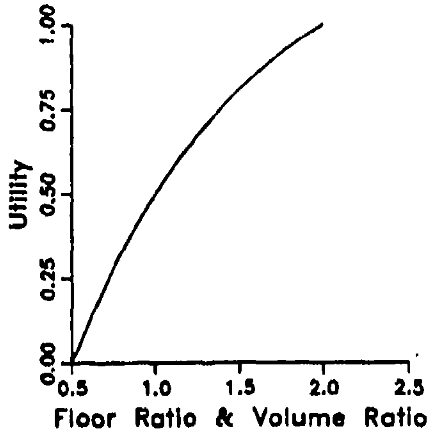


f. Attribute B.2

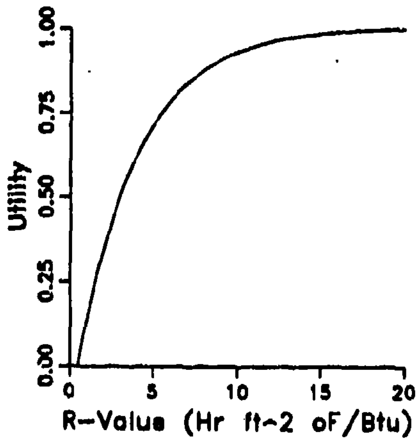
Figure 112. Continuous Single Attribute Utility Functions Used in ASEM.



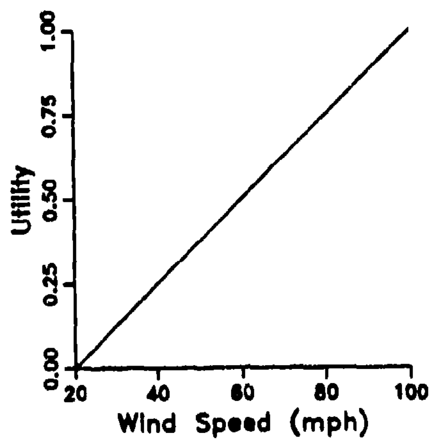
g. Attribute B.3



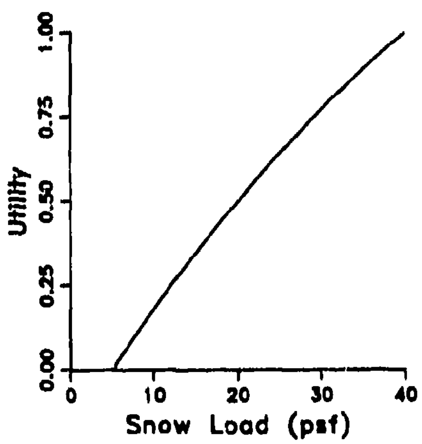
h. Attributes C.1.1.1 and C.1.1.2



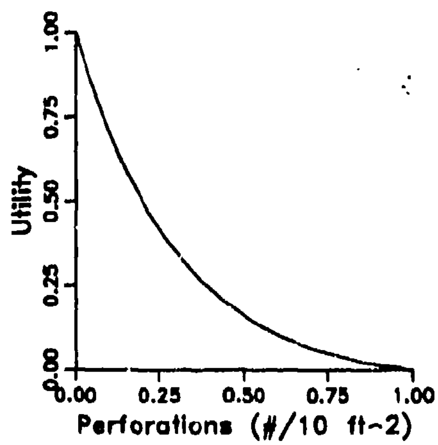
i. Attribute C.3.1



j. Attribute C.3.2.1



k. Attribute C.3.2.2



l. Attribute D.1.1

Figure 112. Continuous Single Attribute Utility Functions Used in ASEM (Continued).

Worst value = 4 *pounds/foot*^{3}
Best value = 0.05 *pounds/foot*^{3}
Median value = 0.5 *pounds/foot*^{3}
ORD threshold = none
ORD objective = none

A.1.3 ***463L Compatibility (Constraint).*** Shelters must be transportable in standard 108-*inch* × 88-*inch* × 96-*inch* 463L pallets. In addition, the total weight for a single pallet cannot exceed 10,000 *pounds*.

A.2.1 ***Man-Hours.*** Number of *man-hours* (MH) needed to assemble the shelter for every 75 *feet*^{2} of erected floor space.

Worst value = 12 *man-hours/75 feet*^{2}
Best value = 0.2 *man-hours/75 feet*^{2}
Median value = 0.8 *man-hours/75 feet*^{2}
ORD threshold = 1.0 *man-hours/75 feet*^{2}
ORD objective = 0.75 *man-hours/75 feet*^{2}

A.2.2 ***Heavy Equipment*** . Number of equipment-hours (EH) needed to assemble the shelter for every 600 *feet*^{2} of erected floor space.

Worst value = 10 *equipment-hours/600 feet*^{2}
Best value = 0 *equipment-hours/600 feet*^{2}
Median value = 1 *equipment-hours/600 feet*^{2}
ORD threshold = No heavy equipment needed for small shelters
ORD objective = None

A.2.3 ***Labor Skills (Constraint).*** Assembly of small and medium shelters shall require no specialized training.

ORD threshold = Minimal training for all shelter types
ORD objective = No training required for small shelters

B.1 ***Unit Cost.*** The initial unit cost of a shelter expressed in terms of dollars per *foot*^{2} of usable floor space.

Worst value = \$600/*foot*^{2}
Best value = \$1/*foot*^{2}
Median value = \$100/*foot*^{2}
ORD threshold = TBD
ORD objective = TBD

B.2 ***Redeployment Costs.*** Cost of expendable shelter components that must always be replaced before the shelter can be redeployed plus the expected cost of damaged or lost components that must be replaced before the shelter can be redeployed. Redeployment costs are estimated as a percentage of the initial total cost of the shelter.

Worst value = 100 *percent*
Best value = 0 *percent*
Median value = 20 *percent*
ORD threshold = TBD
ORD objective = TBD

B.3 ***Life Cycle.*** The life cycle is specified as the expected number of deployments over the life of the shelter. Our estimates are based on the following assumptions: (1) no damage occurs while the shelters are in storage, (2) the average duration of deployment is 2 *months*, and (3) the shelters will most often be deployed in a non-extreme climate/environment.

Worst value = 1 deployment
Best value = 30 deployments
Median value = 12 deployments
ORD threshold = 12 deployments over a 20-*year* life cycle
ORD objective = 26 (small) or 20 (large) deployments over a 20-*year* life cycle

C.1.1.1 ***Floor Space Ratio.*** The ratio of provided usable floor space to minimum required floor space. (600 $feet^2$ for small shelters; 4800 $feet^2$ for hangars)

Worst value = 0.5
Best value = 2.0
Median value = 1.0
ORD threshold = None
ORD objective = None

C.1.1.2 ***Volume Ratio.*** Ratio of provided usable volume to minimum required volume (4800 $feet^3$ for small shelters; 72,000 $feet^3$ for hangars).

Worst value = 0.5
Best value = 2.0
Median value = 1.0
ORD threshold = None
ORD objective = None

C.1.2 ***Extendability and Modularity.*** This attribute reflects the ability of a shelter to adapt to changing functions and variable space requirements. An extendable shelter can be enlarged by adding repetitive units end to end (*e.g.*, adding bays to an arch structure). Similarly, modular structures are pre-designed to be easily interconnected to form larger spaces. Since no interior partitions or supports are created when the length of an extendable shelter is increased, extendability may be preferable to modularity in some cases.

0 *points* = Complex, non-modular 3-D structure
30 *points* = Limited complexity 3-D structure (*e.g.*, dome)
60 *points* = Simple 3-D structure (*e.g.*, box)
90 *points* = Smooth 2-D structure (*e.g.*, arch)

100 *points* = Segmented 2-D structure (*e.g.*, plane frame)
ORD threshold = None
ORD objective = Modular, extendable, convertible, and inter-connectable

C.2 ***Habitability.*** Working/living conditions inside the shelter directly impact the productivity and morale of the occupants. This attribute considers some of the design aspects that may impact shelter habitability. The score for this attribute is obtained by summing over the applicable characteristics:

35 *points* = Hinged doors
30 *points* = Rigid floor
20 *points* = Rigid walls
15 *points* = Rigid roof
ORD threshold = Expedient flooring
ORD objective = Rigid floors and hinged doors

C.3.1 ***R-Value.*** Average R-Value measures the overall insulation level provided by the shelter.

Worst value = 0.5 (*hour feet*^{2} °F/*Btu*)
Best value = 20 (*hour feet*^{2} °F/*Btu*)
Median value = 5 (*hour feet*^{2} °F/*Btu*)
ORD threshold = None
ORD objective = Minimize HVAC demand

C.3.2.1 ***Windspeed.*** Windspeed is defined as the maximum sustained windspeed that can be safely resisted by the shelter.

Worst value = 20 *miles /hour*
Best value = 100 *miles /hour*
Median value = 60 *miles /hour*
ORD threshold = 80 *miles /hour*(sustained), 100 *miles /hour* (gust)
ORD objective = None

C.3.2.2 ***Snow Load.*** Snow load is defined as the maximum snow load that can be safely resisted by the shelter.

Worst value = 5 *pounds/foot*^{2}
Best value = 40 *pounds/foot*^{2}
Median value = 20 *pounds/foot*^{2}
ORD threshold = 10 *pounds/foot*^{2}
ORD objective = None

C.4 ***Reliability and Maintainability (For Future Use).*** The following attributes cannot be adequately assessed at this phase of development. Therefore, the attributes are only included for future reference. It should also be noted that the reliability and maintainability attributes should have separate specifications at the field and depot levels.

C.4.1 *Durability (For Future Use).* Mean time between failures for all shelter components should be minimized.

C.4.2 *Repairability (For Future Use).* Mean time required to repair any damaged shelter components should be minimized.

C.4.2 *Maintainability (For Future Use).* Maintenance requirements for shelters should be minimized in both the storage mode and the deployed mode.

D.1.1 *Perforation.* The expected number of shelter perforations per 10 *feet*^{2} of exposed surface area for a specified fragmenting weapon threat. The threat for this study is taken to be a surface burst of a vertical cluster munition at a standoff of 100 *feet*.

Worst value = 1.0 perforations/10 *feet*^{2}
Best value = 0.0 perforations/10 *feet*^{2}
Median value = 0.2 perforations/10 *feet*^{2}
ORD threshold = Splinter protection
ORD objective = Potential for semi-hardened

D.1.2 *Impulse (For Future Use).* The equivalent uniform impulse that can be sustained by the shelter without loss of function should be maximized. The combined effects of airblast and fragment impulses should be considered.

D.1.3.1 *Blackout (Constraint).* Shelter must meet blackout requirements specified in the ORD.

D.1.3.2 *Electronic Shielding (For Future Use).* For some shelter functions (*e.g.*, C3), EMI shielding may be an objective; however, this attribute is not addressed in the current implementation of ASEM.

D.1.3.3 *Infrared Detectability (For Future Use).* For some shelter functions (*e.g.*, C3), reducing the IR signature may be an objective; however, this attribute is not addressed in the current implementation of ASEM.

D.2.1 *Air Leakage Rate. (For Future Use)* Air leakage rate in *feet*^{3}*/minute* while maintaining an overpressure of 0.3 *inches* of water.

D.2.2 *Decontamination Time. (For Future Use)* Over a range of specified chemical and biological weapon threats, the maximum expected number of man-hours required to decontaminate the shelter per 100 *feet*^{2} of exposed surface area.

3. Preference Sets

To assess the candidate shelter concepts in ASEM, a set of decision-maker (DM) preferences must be supplied as one of the inputs. The preferences or values of the DM are represented via the scaling constants and the interaction constants (see Section IV.B). The AF has not designated a DM (or group of AF DMs) to supply a preference set for the objectives listed in the FOPS ORD. In lieu of an AF supplied preference set, we have developed four sets of scaling constants for the ASEM trade studies.

The preference sets developed for the shelter evaluation studies are based on our interactions with members of the AF portable shelter user community and on information obtained during our review of existing shelter technologies. The overall shelter utilities generated from the four preference sets and the marginal shelter utilities generated the four first-level objectives provide the basis for the comparison and selection of the candidate concepts in Section IV.E.

In the first preference set, the high-level scaling constants are based on the results of a survey of AF personnel who attended the FOPS Requirements Working Group (RWG) meeting[1]. In the second preference set, the four first-level objectives described in Section IV.C.1 were assigned equal scaling constants. These two sets of scaling constants shall be referred to as the RWG preference set and the Equal preference set, respectively. The third and fourth preference sets are bounding cases. In the third set, the scaling constant for survivability has been set to zero, and in the fourth set, the scaling constant for cost has been set to zero. In both cases, the remaining three first-level scaling constants have been assigned equal values (*i.e.*, one-third). The third and fourth preference sets shall be referred to as the No-Cost and No-Survivability preference sets, respectively.

We did not have the opportunity to explore the question of attribute independence via question and answer sessions with a designated DM or group of DMs. Therefore, we have proceeded with the assumption that the shelter attributes satisfy additive independence. Under additive independence, the scaling constants must sum to one for each group of attributes at a given level in the hierarchy, and the multiplicative interaction constant is zero. Additive independence is frequently assumed in multi-attribute decision analyses, even if it cannot be fully confirmed. As discussed in Section IV.B.2, a well-constructed hierarchy will often reduce attribute interactions. In addition to reducing the complexity involved in assessing a DM's preference set, the assumption of additive independence simplifies the interpretation of the analysis results.

Even under the assumption of additive independence, one must not conclude that the scaling constants are simple weighting factors applied to each attribute. The scaling constants are applied to the utilities of the individual attributes which, in general, are nonlinear functions of the actual attribute value. Since DMs almost always express some degree of risk aversion for at least some of the design attributes, nonlinearities are virtually certain to propagate into the overall utility function. A proper interpretation of a scaling constant is that it represents the relative importance of moving from the worst value of an attribute to its best value. This interpretation is valid since the marginal utilities associated with the best and worst values are by definition 1.0 and 0.0, respectively. Therefore, scaling constants depend on the ranges of worst

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[1]The detailed results of the RWG follow-up survey are presented in Appendix C.

to best values. The range over which a single attribute utility function is defined should not be changed without reassessing the scaling constants at that level.

The four preference sets are summarized in Table 32. Since the RWG survey produced complete data only for the first-level objectives (*i.e.*, mobility, cost, performance, and survivability), we did not obtain direct AF input on the preferences below the first level. As a result, the lower-level scaling constants are identical in each of the four preference sets and reflect our best estimates of the relative importance attached to each attribute by the AF portable shelter user community. Obviously, there is a potential for strong disagreements between individual members of the shelter community. The significant scatter observed in the RWG survey responses are evidence of this potential. We recommend that as the shelter concepts become more clearly defined follow-up surveys should be conducted to assess the range of AF preferences.

D. BASIC AND UPGRADED DESIGN CONCEPT ATTRIBUTES

In this section, we briefly summarize the attribute values used in the ASEM analyses of the small and large shelter concepts. Attribute values are specified for both the basic (*i.e.*, non-upgraded) and upgraded shelter configurations.

1. Basic Shelter Attributes

Best estimate or median values for the attributes of the 16 basic small shelter concepts and eight basic portable hangar concepts were listed previously in Tables 8 and 11 (Section II.D). These estimates are based on our review of existing shelter technology. Since there is considerable uncertainty associated with many of the design variables, we have also developed optimistic and pessimistic estimates for each of the candidate design concepts.[1] Thus, for each basic shelter concept, three sets of expected utilities are generated in Section IV.E. Selected optimistic and pessimistic design attribute values are summarized for each concept in Tables 33 through 36.[2] We shall also refer to the best estimate, optimistic, and pessimistic attribute estimates as the median, high, and low attributes, respectively.

2. Upgraded Shelter Survivability Attributes

Based on the fragment-hardening studies presented in Section III.G we have selected four standard hardening upgrades to be included in the ASEM analyses: (1) a 36-*inch* thick free-standing soil bin or shelter-supported soil berm, (2) free-standing or shelter-supported aluminum panels with an areal density of 4 *pounds/foot*^{2} (*psf*), (3) free-standing or shelter-

[1] Because the SAFE fragment perforation model has not yet been validated, we did not attempt to develop optimistic or pessimistic bounds for the survivability attributes for either the basic or upgraded shelter concepts. Experiments planned for the next phase of the airmobile shelter research program are expected to provide the data needed to characterize biases and variabilities in the survivability design attributes.

[2] Attributes not listed in Tables 33 through 36 are assumed to be deterministic. Therefore, the median values tabulated in Section II.D are used for these attributes.

TABLE 32. PREFERENCE SETS USED IN ASEM.

Attribute/Objective	Units	Attribute Range		Preference Set			
		Worst	Best	RWG	Equal	No Surv.	No Cost
Mobility	n/a	n/a	n/a	0.36	0.25	0.33	0.33
Cost	n/a	n/a	n/a	0.12	0.25	0.33	0.00
Performance	n/a	n/a	n/a	0.39	0.25	0.33	0.33
Survivability	Perf./10 $feet^2$	1.00	0.00	0.13	0.25	0.00	0.33
Transportability	n/a	n/a	n/a	0.67	0.67	0.67	0.67
Assembly Time	n/a	n/a	n/a	0.33	0.33	0.33	0.33
Packing Ratio	$feet^3/foot^3$	3	500	0.67	0.67	0.67	0.67
Weight Ratio	$pounds/foot^3$	4	0.05	0.33	0.33	0.33	0.33
Man-Hours	MH/75 $foot^2$	12	0.2	0.67	0.67	0.67	0.67
Equipment-Hours	EH/600 $foot^2$	10	0	0.33	0.33	0.33	0.33
Unit Cost	$\$/foot^2$	600	0	0.50	0.50	0.50	0.50
Redepl. Cost	*Percent*	100	0	0.25	0.25	0.25	0.25
Life Cycle	# Deploy.	1	30	0.25	0.25	0.25	0.25
Geometry	n/a	n/a	n/a	0.35	0.35	0.35	0.35
Habitability	See Text	None	All	0.25	0.25	0.25	0.25
Environmental Perf.	n/a	n/a	n/a	0.40	0.40	0.40	0.40
Interior Space	n/a	n/a	n/a	0.33	0.33	0.33	0.33
Modularity	See Text	Complex 3-D	Simple 2-D	0.67	0.67	0.67	0.67
Floor Space Ratio	$feet^2/foot^2$	0.5	2	0.50	0.50	0.50	0.50
Volume Ratio	$feet^3/foot^3$	0.5	2	0.50	0.50	0.50	0.50
R-Value	$Hour\ feet^2$ °F/Btu	0.5	20	0.35	0.35	0.35	0.35
Structural	n/a	n/a	n/a	0.65	0.65	0.65	0.65
Design Wind Speed	*mph*	20	100	0.50	0.50	0.50	0.50
Design Snow Load	*psf*	5	40	0.50	0.50	0.50	0.50

supported 4 *psf* S2-glass reinforced composite panels, and (4) 4 *psf* shelter-supported Spectra® blankets. These four upgrades constitute a representative sampling of the hardening upgrades evaluated in Section III. The mobility and cost attributes for the four selected hardening upgrades are summarized in Table [illegible]. The tabulated values are estimates for the changes in the basic shelter attributes per 100 $feet^2$ of protected vertical wall area. The upgrades are assumed to protect the lowest 8 vertical *feet* around the perimeters of the small shelters and the lowest 15 vertical *feet* around the perimeters of the large shelters.

The weapon threat selected to evaluate hardness of the four upgrades is a surface burst of a vertically oriented cluster munition at a standoff of 100 *feet* from the mid-point of the

TABLE 33. OPTIMISTIC DESIGN ATTRIBUTE ESTIMATES FOR THE BASIC SMALL SHELTER CONCEPTS.

Attribute	Units	Concept Number							
		1	2	3	4	5	6	7	8
Packing Ratio	*feet*^{3}/*feet*^{3}	137.87	52.78	42.23	422.27	142.66	105.57	21.11	7.79
Weight Ratio	*pounds/feet*^{3}	0.09	0.29	0.39	0.05	0.12	0.12	0.49	0.89
Man-Hours	MH/75 *feet*^{2}	0.23	0.70	0.70	0.23	0.47	0.35	1.17	0.95
Equipment-Hours	EH/600 *feet*^{2}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Unit Cost	$/*feet*^{2}	3.13	12.50	12.50	4.69	12.50	6.25	93.75	63.56
Redepl. Cost	*Percent*	10.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Life Cycle	# Deploy.	12.00	20.00	20.00	18.00	18.00	18.00	24.00	30.00
R-Value	*Hr feet*^{2} °F/Btu	2.00	2.00	2.00	2.00	4.00	2.00	4.00	5.00
Wind Speed	*mph*	60.00	100.00	60.00	60.00	60.00	60.00	80.00	100.00
Snow Load	*psf*	10.00	30.00	20.00	15.00	15.00	15.00	25.00	40.00
Attribute	Units	Concept Number							
		9	10	11	12	13	14	15	16
Packing Ratio	*feet*^{3}/*feet*^{3}	9.72	20.29	52.78	31.99	15.76	81.15	52.78	15.39
Weight Ratio	*pounds/feet*^{3}	0.69	0.41	0.39	0.39	0.98	0.57	0.39	0.60
Man-Hours	MH/75 *feet*^{2}	0.89	2.93	2.81	2.81	4.69	1.46	1.88	1.92
Equipment-Hours	EH/600 *feet*^{2}	0.00	0.00	3.94	3.94	7.50	0.00	0.00	0.00
Unit Cost	$/*feet*^{2}	46.65	48.78	6.25	12.50	78.[illegible]	6.50	6.25	48.00
Redepl. Cost	*Percent*	5.00	5.00	30.00	15.00	15.00	100.00	100.00	5.00
Life Cycle	# Deploy.	27.00	24.00	20.00	10.00	10.00	1.00	1.00	24.00
R-Value	*Hour feet*^{2} °F/Btu	3.00	5.00	8.00	4.00	20.00	15.00	2.00	5.00
Wind Speed	*mph*	100.00	100.00	80.00	80.00	100.00	100.00	100.00	100.00
Snow Load	*psf*	30.00	40.00	30.00	30.00	40.00	40.00	40.00	40.00

longer shelter wall. The numbers of fragment perforations per 10 *feet*^{2} of exposed wall area for this threat and an array of 28 different wall types are listed in Table 38. In addition to the four hardening upgrades, three additional materials are listed: (1) conventional polyester fabric (*i.e.*, zero protection), (2) 1 *psf* aluminum, and (3) 12 *inches* of soil. Fabric and lightweight aluminum are representative non-upgraded cladding materials. The 12-*inch* soil wall is used to characterize the block wall and bin wall shelter concepts.

Recall from Section C.2 that the fragmentation survivability attribute has units of perforations per 10 *feet*^{2} of exposed surface area. Obviously, the best value for the survivability attribute is zero perforations per 10 *feet*^{2}. We have selected the worst value to be 1.0 perforations per 10 *feet*^{2}, and we have estimated the median value to be 0.2 perforations per 10

TABLE 34 PESSIMISTIC DESIGN ATTRIBUTE ESTIMATES FOR THE BASIC SMALL SHELTER CONCEPTS.

Attribute	Units	Concept Number							
		1	2	3	4	5	6	7	8
Packing Ratio	*feet*^{3}/*feet*^{3}	61.58	31.99	21.11	105.57	84.45	63.21	10.56	5.84
Weight Ratio	*pounds/feet*^{3}	0.13	0.49	0.59	0.16	0.20	0.20	0.88	1.63
Man-Hours	MH/75 *feet*^{2}	0.47	1.17	1.17	0.47	0.94	0.70	1.76	1.69
Equipment-Hours	EH/600 *feet*^{2}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Unit Cost	\$/*feet*^{2}	6.25	23.44	25.00	7.81	23.44	9.38	156.25	112.99
Redepl. Cost	*Percent*	20.00	20.00	20.00	20.00	20.00	20.00	15.00	15.00
Life Cycle	# Deploy.	8.00	8.00	8.00	12.00	12.00	12.00	12.00	18.00
R-Value	*Hour feet*^{2} °F/Btu	0.50	0.50	0.50	0.50	1.00	0.50	2.00	3.00
Wind Speed	*mph*	40.00	60.00	40.00	40.00	40.00	40.00	60.00	60.00
Snow Load	*psf*	10.00	10.00	10.00	5.00	5.00	5.00	10.00	40.00

Attribute	Units	Concept Number							
		9	10	11	12	13	14	15	16
Packing Ratio	*feet*^{3}/*feet*^{3}	7.78	6.76	31.99	10.56	7.04	40.58	31.99	6.87
Weight Ratio	*pounds/feet*^{3}	1.17	0.81	0.59	0.98	1.46	0.73	0.59	0.90
Man-Hours	MH/75 *feet*^{2}	1.43	4.88	4.69	4.69	9.38	2.93	2.81	2.88
Equipment-Hours	EH/600 *feet*^{2}	0.00	0.00	3.94	3.94	7.50	0.00	0.00	0.00
Unit Cost	\$/*feet*^{2}	79.53	130.08	12.50	23.44	156.25	13.01	11.72	128.00
Redepl. Cost	*Percent*	15.00	15.00	30.00	30.00	40.00	100.00	100.00	15.00
Life Cycle	# Deploy.	15.00	12.00	8.00	5.00	4.00	1.00	1.00	12.00
R-Value	*Hour feet*^{2} °F/Btu	1.00	3.00	4.00	2.00	10.00	8.00	1.00	3.00
Wind Speed	*mph*	60.00	60.00	50.00	60.00	100.00	60.00	60.00	60.00
Snow Load	*psf*	10.00	40.00	10.00	10.00	40.00	20.00	20.00	40.00

TABLE 35. OPTIMISTIC DESIGN ATTRIBUTE ESTIMATES FOR THE BASIC LARGE SHELTER CONCEPTS.

Attribute	Units	Concept Number							
		1	2	3	4	5	6	7	8
Packing Ratio	*feet*^{3}/*feet*^{3}	148.45	153.40	464.85	228.96	306.80	51.13	74.23	25.57
Weight Ratio	*pounds/feet*^{3}	0.06	0.05	0.05	0.08	0.07	0.31	0.16	0.81
Man-Hours	MH/75 *feet*^{2}	0.63	0.60	0.30	0.48	0.48	1.21	1.25	1.81
Equipment-Hours	EH/600 *feet*^{2}	0.00	0.00	0.00	0.00	0.00	0.00	2.63	1.94
Unit Cost	\$/*feet*^{2}	4.17	4.03	6.05	8.06	10.08	40.32	15.63	5.04
Redepl. Cost	*Percent*	5.00	5.00	5.00	5.00	5.00	5.00	10.00	100.00
Life Cycle	# Deploy.	20.00	20.00	18.00	18.00	18.00	30.00	15.00	1.00
R-Value	*Hour feet*^{2} °F/Btu	2.00	2.00	2.00	4.00	2.00	5.00	4.00	2.00
Wind Speed	*mph*	100.00	100.00	60.00	60.00	60.00	100.00	100.00	100.00
Snow Load	*psf*	30.00	30.00	15.00	15.00	15.00	40.00	30.00	40.00

TABLE 36. PESSIMISTIC DESIGN ATTRIBUTE ESTIMATES FOR THE BASIC LARGE SHELTER CONCEPTS.

Attribute	Units	Concept Number							
		1	2	3	4	5	6	7	8
Packing Ratio	*feet*^{3}/*feet*^{3}	74.23	76.70	153.40	102.27	153.40	38.35	49.48	19.18
Weight Ratio	*pounds*/*feet*^{3}	0.16	0.13	0.10	0.13	0.13	0.50	0.27	1.08
Man-Hours	MH/75 *feet*^{2}	1.25	1.21	0.48	0.91	0.73	1.81	1.88	3.02
Equipment-Hours	EH/600 *feet*^{2}	0.00	0.00	0.00	0.00	0.00	0.00	2.63	1.94
Unit Cost	$/*feet*^{2}	20.83	20.16	10.08	16.13	20.16	161.29	31.25	12.10
Redepl. Cost	*Percent*	20.00	20.00	20.00	20.00	20.00	15.00	25.00	100.00
Life Cycle	# Deploy.	8.00	8.00	12.00	12.00	12.00	18.00	8.00	1.00
R-Value	*Hour feet*^{2} °F/Btu	0.50	0.50	0.50	1.00	0.50	3.00	2.00	1.00
Wind Speed	*mph*	60.00	60.00	40.00	40.00	40.00	80.00	60.00	60.00
Snow Load	*psf*	10.00	10.00	5.00	5.00	5.00	30.00	10.00	20.00

TABLE 37. SHELTER UPGRADE ATTRIBUTES PER 100 *FEET*^{2} PROTECTED AREA.

Upgrade	(1) Volume (*feet*^{3})	(2) Weight (*pounds*)	(3) Man-Hours	(4) Equipment-Hours	(5) Cost ($1000)[b]
1. 36-*inch* Soil					
a. Free-Standing Bin[c]	40[a]	750[a]	6	1	1.1
b. Berm	8[a]	125[a]	2	0.5	0.1
2. 4-*psf* Aluminum					
a. Free-Standing	40	750	2	0	3.6
b. Shelter-Supported	25	500	1	0	2.4
3. 4-*psf* S2-glass Panel					
a. Free-Standing	40	750	2	0	10.8
b. Shelter-Supported	25	500	1	0	9.6
4. 4-*psf* Blanket					
a. Shelter-Supported	8	400	0.5	0	36.0

[a] Includes equipment weight and volume estimates at a rate of 1 scoop loader per 80 *equipment-hours*.
[b] Estimated finished costs: Aluminum = $6/*pound*; S2-glass = $24/*pound*; and Spectra® = $90/*pound*.
[c] Sources: Army FM 5-103 [1985] and Sues, *et al.* [1991].

feet^2. The exponential perforation utility function used in ASEM was shown in Figure 113(a). The reasoning behind the normalization of the perforation attribute is that 10 *feet*^{2} conservatively approximates the presented area of an individual. Thus, one perforation per 10 *feet*^{2} implies that the likelihood of an occupant being hit by a fragment is high. We selected the cluster munition standoff such that an unprotected shelter wall would have a survivability attribute of approximately zero, and we selected a median value of 0.2 perforations per 10 *feet*^{2} to ensure

TABLE 38. EXPECTED NUMBER OF FRAGMENT PERFORATIONS PER 10 *FEET*^{2} OF EXPOSED WALL AREA FOR A CLUSTER MUNITION AT A 100-*FOOT* STANDOFF.

Cladding	Shelter Size and Wall Orientation			
	Small (32 × 8 *feet*)		Large (80 × 15 *feet*)	
	Vertical	Inclined[a]	Vertical	Inclined[b]
Conventional Fabric	0.83	0.83	0.69	0.68
1 *psf* Aluminum	0.57	0.55	0.47	0.43
12-*inch* Soil	0.23	0.18	0.18	0.11
36-*inch* Soil	0.00	0.00	0.00	0.00
4 *psf* Aluminum	0.34	0.29	0.27	0.21
4 *psf* S-2 Panel	0.14	0.12	0.11	0.09
4 *psf* Spectra® Blanket	0.14	0.14	0.12	0.11

[a] Wall slopes 4 *feet* away from the weapon in a vertical run of 8 *feet*.
[b] Wall slopes 10 *feet* away from the weapon in a vertical run of 15 *feet*.

that the utility of a hardening upgrade begins to increase significantly only after an appreciable increase in individual survival probability is achieved.[1]

For the composites, a cost multiplier of 3.0 has been applied to our best available information on the raw fiber cost to obtain an estimate of the finished cost. Our relative cost estimates for the hardening upgrades are generally in-line with other published cost data [Schuman, 1991; Fanucci, 1982; Bless, *et al.*, 1986; and Frank, *et al.*, 1989].

E. ASEM RESULTS

Having described the ASEM approach, objectives hierarchy, and inputs in Sections B, C, and D, we now proceed to the shelter evaluation results. First, we present the results for the basic and upgraded small shelter concepts. Following the small shelter results, we assess the basic and upgraded portable hangar concepts.

In our presentation of the small shelter results, we will refer to Figures 113 through 115. Similarly, we will refer to Figures 116 through 118 in our discussion of the large shelter results. Each of the plots in these figures shows some measure of shelter value or utility on the vertical axis *vs.* concept number on the horizontal axis. The performance measures plotted in two groups of figures for the small and large shelter concepts are summarized in the following paragraphs.

Results for three of the four primary shelter objectives as well as two physical measures of shelter mobility are illustrated in Figures 113 and 116 for the basic small and large shelters, respectively. Three points are shown on each plot for each of the shelter concepts. The three

[1] A more rigorous treatment of survival probabilities that will include casualty models should be conducted during the prototype development phase.

points correspond to the low, median, and high attribute estimates discussed in Section IV.D. The five plots shown in Figures 113 and 116 are:

a. Mobility utility
b. Cost utility
c. Basic shelter performance utility
d. Number of C-130s required for transport
e. Number of worker-days required for assembly

Plots a, b, and c in the two figures illustrate the utilities of each shelter concept with respect to three of the four first-level objectives: mobility, cost, and basic shelter performance. Concepts with higher relative utilities have better combinations of the attributes that characterize the primary objective being considered. The transport demand and assembly demand plots, on the other hand, are physical (*i.e.*, dimensional) measures of shelter mobility. Transport demand (Figures 113.d and 116.d) is defined as the number of C-130s needed to transport 50,000 *square feet* of usable shelter space (*i.e.*, approximately 80 small shelters or 10 hangars). Thus, transport demand is inversely proportional to the shelter packing ratio attribute. Similarly, the assembly demand (Figures 113.e and 116.e) is defined as the number of worker-days required to assemble 50,000 square *feet* of usable shelter space. These values are directly proportional to the shelter assembly rate attribute. Shelter utility with respect to the mobility objective is closely related to the combined performance of the concept with respect to its transport and assembly demands.

The median mobility, cost, performance, and survivability attributes of the basic and upgraded shelter concepts are shown in Figures 114 and 117 or the small and large shelters, respectively. In each plot, up to five points are shown for each basic shelter concept, corresponding to the basic shelter configuration and up to four applicable upgraded configurations (see Section IV.D.2). Thus, the plots illustrate the impact of the four selected hardening upgrades on shelter utility for each of the four first-level objectives.

The median overall utilities of the basic and upgraded shelter concepts are summarized in Figures 115 and 118 for the small and large shelters, respectively. These figures illustrate the combined overall utilities of each basic or upgraded shelter configuration under the four different preference sets discussed in Section IV.C.3: (a) RWG scaling, (b) Equal Scaling, (c) No-Survivability scaling, and (d) No-Cost scaling. These plots form the primary basis for our shelter recommendations.

1. Small Shelter Concepts[1]

a. Mobility, Cost, and Performance — Basic Concepts Only (*Figure 113*)

Mobility. The mobility objective is comprised of two major sub-objectives: rapid assembly and transportability. Physical measures of shelter performance with respect to these sub-objectives are illustrated in plots d and e of Figure 113 The transport demand and assembly demand plots clearly display the combined benefits of fabric shelters with respect to mobility. None of the other small shelter concepts offer better than average performance with respect to both transportability and rapid assembly. As a result, all of the leading basic shelter concepts with respect to mobility are fabric shelters, regardless of the relative importance placed on transportability and rapid assembly. The air beam concept is the overall leader with excellent packing, weight, and assembly characteristics. In addition to the air-inflated and air-supported fabric shelters, the traditional pole-supported tent also scores highly on mobility. The frame-supported fabric shelter concept, however, falls in the second tier of mobility performance along with the two field manufactured shell concepts (the foam dome and the K-Span personnel shelter). The field manufactured shelter concepts perform well in spite of their relatively slow assembly rates because transport utility has been rated twice as heavily as rapid assembly utility in the ASEM preference sets. All of the remaining shelters are either rigid panel shelters or load bearing wall shelters. With a packing ratio of approximately 6.8:1, the airmobile MERWS concept is the lowest rated of the 16 small-shelter concepts in terms of transport demand. The reinforced earth shelter concept has the slowest assembly rate and a below average packing ratio, making it the lowest rated small shelter concept in terms of overall mobility.

Cost. As with mobility, the leading basic small shelter concepts on the basis of cost are all fabric shelters. However, the variability in cost utilities across the range of shelter concepts is much less than the variability in shelter mobility utilities. The clustering of cost utilities is largely due to the trade-offs between initial costs and subsequent life cycle costs (*i.e.*, shelters having lower initial costs tend to have relatively high redeployment costs and shorter expected life spans). The hybrid MERWS, block wall, airmobile MERWS, and bin wall concepts are the runners up with respect to overall cost. However, heavier relative priorities on expected life span (*i.e.*, number of deployments) and low redeployment costs would pull the MERWS concepts, the hypar shell concept, and the geodesic panel concept to the top of the cost rankings.

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[1]In Section II.D, we noted that there are two dominated small-shelter concepts: the edge-supported stressed membrane shelter (concept 3) is dominated by the frame-supported fabric shelter (concept 2), and the air-supported fabric shelter (concept 6) is dominated by the air beam fabric shelter (concept 4). Therefore, although the results for concepts 3 and 6 are shown for completeness, we will generally omit them from our discussion since they always rank below concepts 2 and 4, respectively.

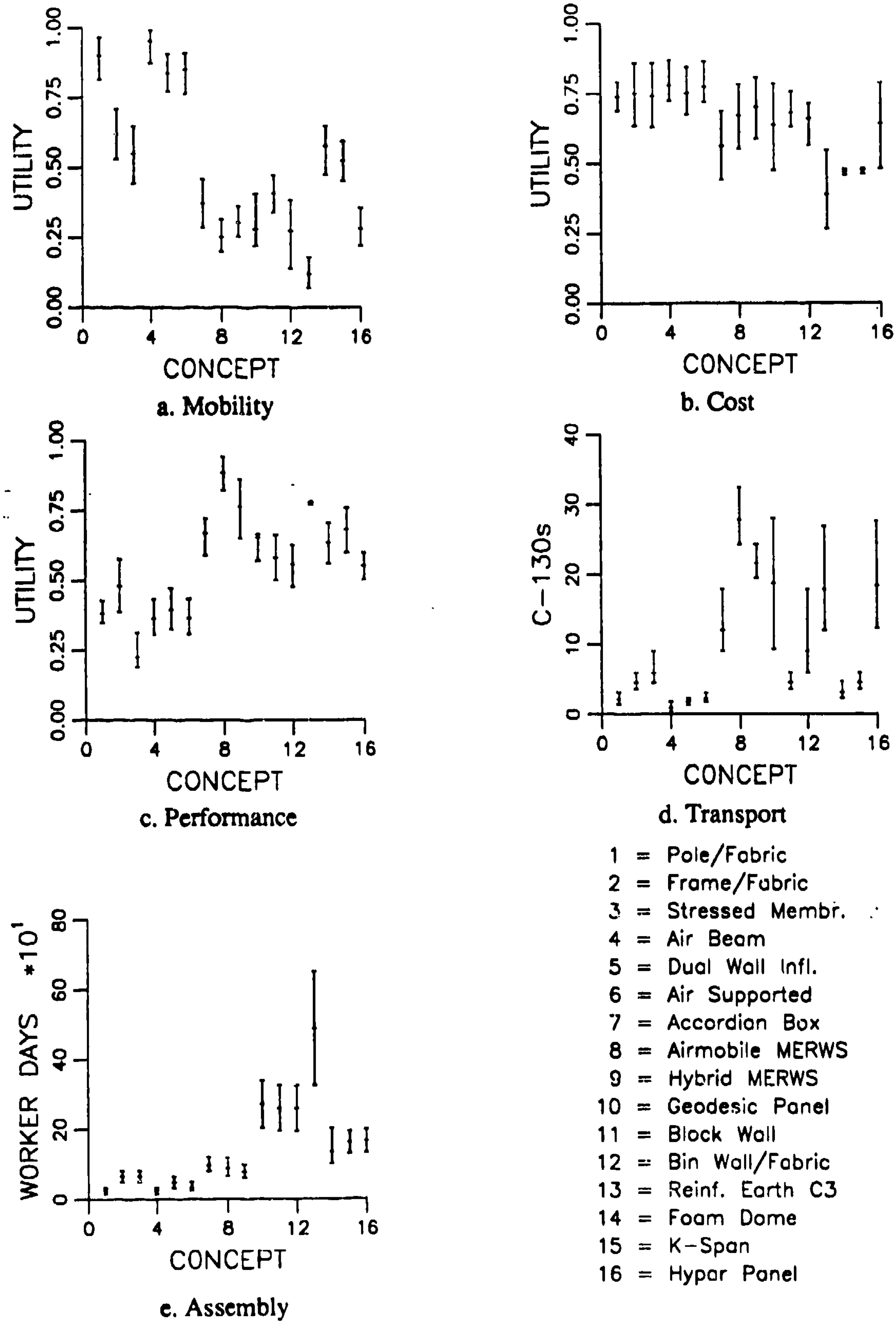


Figure 113. Basic Small Shelter Mobility, Cost, and Performance Results.

Basic Shelter Performance. Basic shelter performance includes geometric design attributes, shelter habitability, and environmental performance factors (*i.e.*, R-value, maximum wind speed, and maximum snow load). The basic performance attributes are the traditional weaknesses of fabric shelters. These weaknesses are borne out by the results shown in Figure 113(c) where the six fabric shelter concept occupy the lowest six positions. Rigid wall shelters, on the other hand, rank highly on basic shelter performance. The airmobile MERWS concept is the clear leader and is followed by the reinforced earth, hybrid MERWS, K-Span, and accordion box concepts. The remaining non-fabric concepts have basic performance utilities ranging from 0.55 to 0.65. Several other basic shelter performance sub-objectives such as operability, maintainability, and durability have not been directly incorporated into the current ASEM hierarchy. As detailed shelter designs and prototype test data become available in future phases of the FOPS development program, we will be able to develop estimates for attributes such as mean time between failures and mean time for repairs. Therefore, we will be able to make better assessments of whether the leading design concepts are meeting the strong preferences for basic shelter performance stated by the RWG survey respondents.

b. Mobility, Cost, Performance, and Survivability — Basic and Upgraded Concepts (*Figure 114*)

With the exception of the three small shelter concepts that directly incorporate soil into their basic configurations (*i.e.*, concepts 11 through 13), none of the basic shelter concepts offers a substantial level of fragment protection. The lightweight rigid wall shelters (*i.e.*, concepts 8-10 and 15-16) provide minimal fragment protection, and the fabric shelters offer virtually no protection. Therefore, we now consider the four representative hardening upgrades described in Section IV.D.2. The relative impacts of the soil, aluminum panel, S2-glass panel, and Spectra® blanket upgrades on the four first-level objectives in the ASEM hierarchy are shown in Figure 114.

The utilities of the hardening upgrades with respect to the survivability objective are essentially independent of the shelter type. In the current SAFE model, the only factor influencing the survivability value of a given upgrade against a given threat is the orientation of the wall. For the aluminum and S2-glass panels, there is some increase in perforation resistance for shelters with inclined walls. The perforation resistance of ballistic fabrics is relatively insensitive to moderate angles of incidence; therefore, we have taken the resistance of Spectra® blanket upgrades to be independent of wall orientation in the current version of SAFE. As noted in Section IV.D.2, the four upgrades span the range of survivability utilities for the selected cluster munition threat. The 36-*inch* soil field-expedient upgrade defeats virtually all of the fragments from the cluster munition and, as a result, has a survivability utility of 1.0. The 4 *psf* S2-glass and Spectra® upgrades provide virtually identical fragment protection, and the 4 *psf* aluminum upgrade provides slightly better protection than the basic shelter configurations. Recall that the block wall and bin wall shelters (concepts 11 and 12) are assumed to have 12 *inches* of soil embedded in their walls in their basic configurations, providing a protection level between that of the aluminum and S2 or Spectra® upgrades.

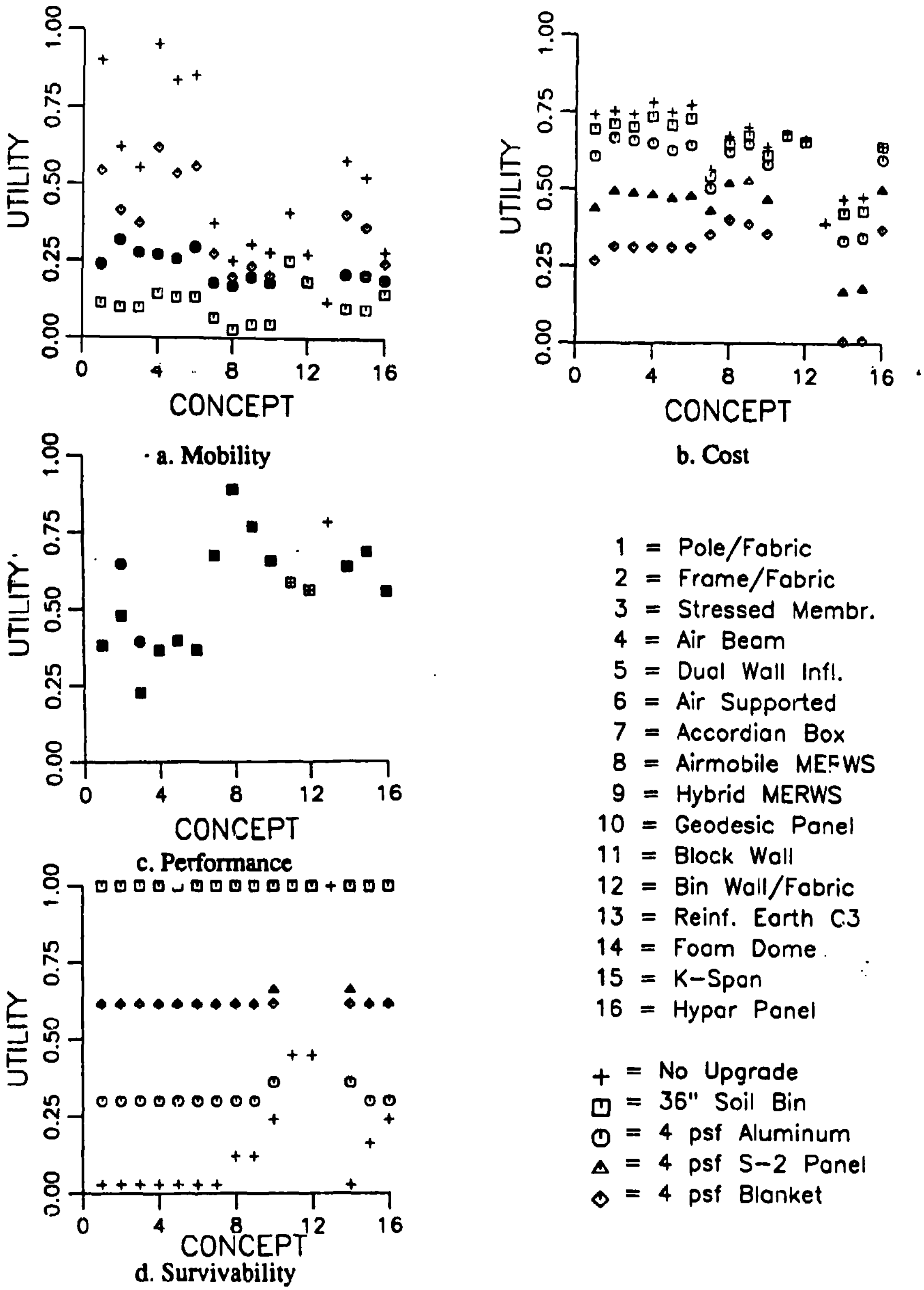


Figure 114. First-Level Results for Basic and Upgraded Small Shelter Concepts.

Mobility and cost utilities are both reduced by the application of the hardening upgrades. Fabric shelters are the most strongly affected since they have the most to lose in terms of both mobility and cost. The shelter-supported Spectra® blanket upgrade is the only hardening method of the four that keeps the fabric shelter mobility utilities in the 0.50 to 0.60 range. However, the Spectra® blankets are also the most expensive survivability measure. Although the cost utilities of the Spectra® upgraded concepts are very poor, it is conceivable that for some shelter applications cost may have a sufficiently low priority relative to mobility and survivability to make the blankets a viable hardening alternative.

For the less expensive S2-glass panel upgrade, the frame-supported fabric shelter is expected to produce a better mobility rating than either air- or pole-supported fabric shelters since the frame-supported fabric shelter can be configured to support the hardening panels. For the other fabric shelter concepts, free standing panel revetments are required, resulting in additional materials and additional assembly time. Soil-based field-expedient hardening upgrades, which are the most effective in terms of survivability, represent another bounding case. These upgrades are cost effective yet demand a high price in terms of assembly and transport. The reinforced earth concept and the upgraded block wall and bin wall shelter concepts provide excellent survivability, reasonable cost, and lower transportation demands than shelters requiring free-standing soil bins. However, assembly time remains a significant drawback for these concepts.

Because the basic rigid panel shelter concepts start out with poor transportability and cost ratings, the impact of hardening upgrades on these concepts is much less severe than in the case of the fabric shelters. Therefore, if survivability is a significant priority, rigid panel shelters can become strong contenders based on their basic shelter performance attributes.

Basic shelter performance is fairly insensitive to the application of hardening upgrades. The lone exception is the frame-supported fabric shelter with shelter-supported panel upgrades. In this case, the upgrades are assumed to provide some improvement in the overall R-Value of the shelter and in its habitability. In general, we can conclude that basic shelter performance is not likely to be degraded by the application of hardening upgrades. Therefore, the performance of nonupgraded shelter configurations will usually be a good indicator of basic shelter performance for a given class of shelters and shelter upgrades.

The tradeoffs in providing survivability are clearly manifested in the marginal utility plots for mobility, cost, and survivability. Therefore, the most desired concept will hinge on the relative importance assigned to each of the first-level objectives. The primary issues are: (1) to what degree can mobility sacrifices be tolerated to achieve hardness?, and (2) what is the relative priority between mobility and basic shelter performance given an environment in which survivability is a high priority?

c. Overall Utility — Basic and Upgraded Concepts (*Figure 115*)

The overall utility results are shown for four different preference sets in Figure 115. Recall that the No-Survivability and No-Cost preference sets are bounding cases in which survivability and cost, respectively, are given zero priority. Similar to the Equal scaling preference set, the remaining three objective in the No-Survivability and No-Cost preference sets are given equal priority. In the RWG scaling set, the priorities assigned to mobility and basic performance are approximately three times as great as either cost or survivability.

Under two of the four preference sets (RWG and No-Survivability), the leading concept is the basic air beam supported fabric shelter. Under RWG scaling, the air beam is followed by the basic pole-supported tent and the soil bin upgraded airmobile MERWS concept. The third tier of concepts includes S2 panel and Spectra® blanket-upgraded MERWS concepts as well as the basic dual wall and air-supported fabric shelter concepts. Under the No-Survivability preference set, basic fabric shelters make up the top five concepts with the air beam and pole-supported concepts leading the way[1]. The fabric shelters are followed by the basic airmobile MERWS and hybrid MERWS concepts. Obviously, none of the upgraded shelter concepts can be expected to rate highly under the No-Survivability scaling since this bounding preference set assigns no priority to shelter hardness. However, it is interesting to note that the highest rated composite hardened shelter concept under the No-Survivability preference set is the S2 panel MERWS which ranks fifteenth overall.

Under the remaining two preference sets (Equal and No-Cost), the airmobile MERWS concept with the free standing 36-*inch* soil bin upgrade is the highest rated concept. Under the Equal scaling set, the MERWS is followed by six other soil hardened concepts: the block wall, hybrid MERWS, bin wall, hypar shell, geodesic dome, and frame-supported fabric shelters, respectively. The runner-ups under the No-Cost scaling are quite similar with the exception that the reinforced earth C3 shelter concept rises to second place. The upgraded block wall shelter concept with 36 *inches* of soil embedded in its field-manufactured wall cells rates in the top ten under the RWG, Equal, and No-Cost preference sets.

If we exclude soil protected shelter concepts from consideration, the MERWS with shelter-supported S2 panels or Spectra® blanket upgrades and the basic air beam shelter become the leading concepts under Equal scaling. As we alluded to in the previous subsection, cost and mobility are the primary drivers in choosing between S2 panels and Spectra® blankets. Preference for low cost favors the S2 panels while preference for mobility favors the Spectra® blankets. Under the RWG scaling (which is mid-way between the Equal and No-Cost preference sets in terms of cost priority) the blankets and S2 panels are equally preferred upgrades for the MERWS concept.

[1]Note that the ASEM model does not have an attribute to account for the obstructed interior space provided by pole-supported tents, and the regular maintenance required to ensure its stability is also not considered. Either of these drawbacks could potentially eliminate the pole-supported tent from consideration.

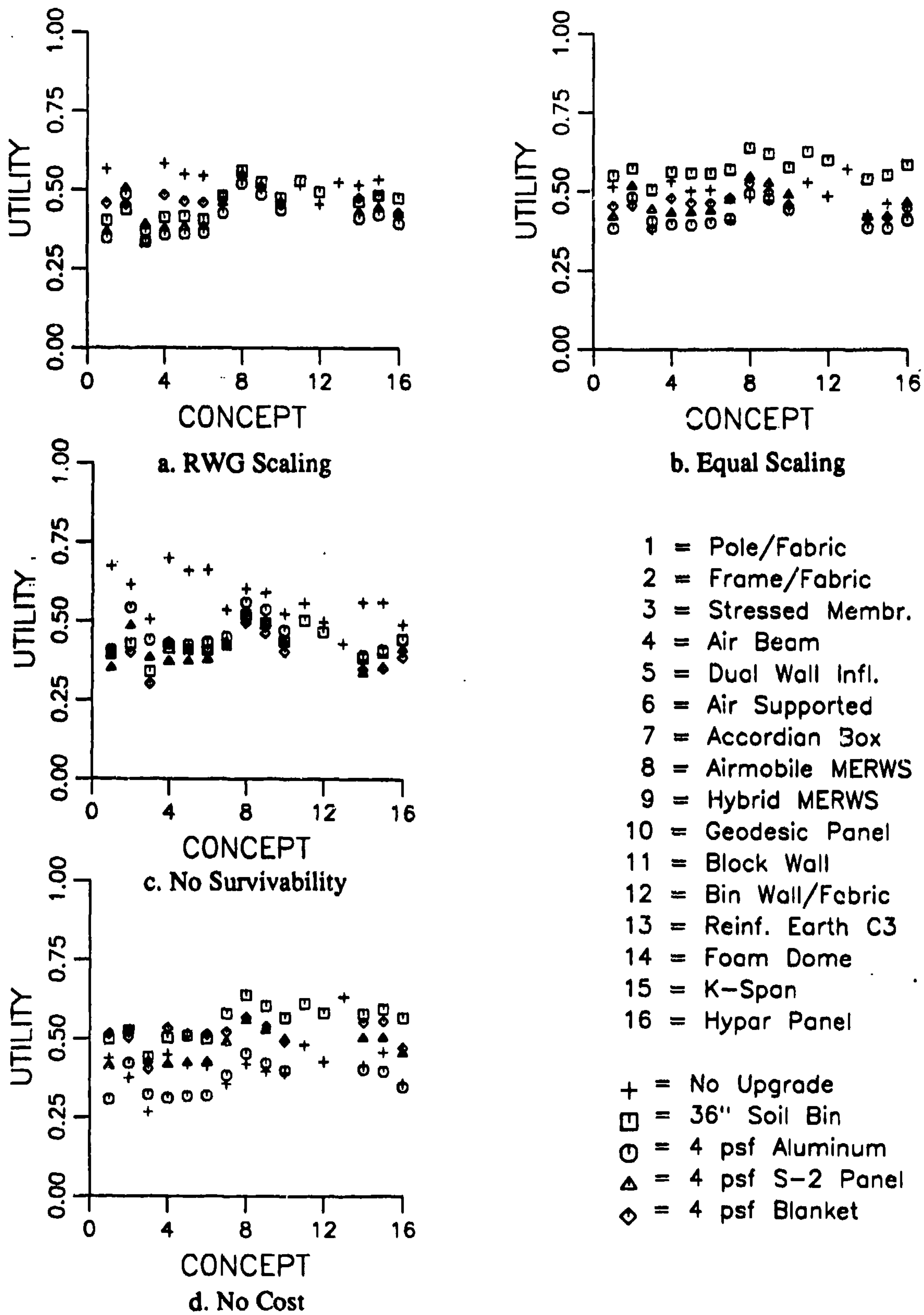


Figure 115. Overall Small Shelter Results.

In summary, three concepts consistently appear at the top of the small shelter overall utility rankings: the basic air beam fabric shelter, the upgraded airmobile MERWS configurations, and the upgraded block wall concept. Of the non-fabric shelters, the airmobile MERWS concept is the leading overall concept for all four preference sets. The block wall shelter, although unproven, is also a potentially successful rigid wall concept. A low risk alternative to the air beam concept is the frame-supported fabric shelter. The frame/fabric concept is the highest rated fabric shelter concept with respect to performance, and it provides balance across all four shelter objectives since it can be designed to accept rigid panel upgrades. Hardening technology developed for the MERWS concepts would also be applicable to an upgraded frame-supported hybrid fabric/panel concept. Thus, the frame-supported fabric concept should be kept under consideration as a low-risk, balanced design alternative.

2. Large Shelter Concepts[1]

a. Mobility, Cost, and Performance — Basic Concepts Only (*Figure 116*)

Mobility. As in the small shelter concepts, the portable hangar concepts dominate the transport demand and assembly demand results shown in Figure 116. The air beam concept is again the best concept in terms of both transport and assembly, and, as a result, it is the overall leader in shelter mobility. The remaining fabric concepts (including the frame- and truss-supported hangars) all score above 0.80 on mobility utility. Although the arch-supported panel and bin wall/fabric roof hangars score reasonably well on mobility, they are well separated from the fabric hangars. The field-manufactured K-Span hangar ranks last due to its significant quantity of steel cladding and its special equipment requirements.

Cost. Here, the results again mirror the small shelter results. Fabric hangars lead the way, but trade-offs between initial costs and subsequent life cycle costs draw the arch/panel and bin wall concepts near to the lower bounds of the fabric concept cost utilities. Increased emphasis on expected life span and low redeployment costs would narrow the gap further between the fabric and rigid wall concepts. Although the K-Span concept rates fairly well on initial costs, its inability to be redeployed (with the exceptions of the corrugating machine and some minor shelter components) severely detracts from its overall cost utility.

Basic Shelter Performance. As with the small shelter concepts, the weaknesses of fabric shelters are found in the basic shelter performance category. The fabric hangars are the lowest five rated concepts in terms of basic performance; however, there is a clear distinction between the air-inflated/air-supported concepts and the frame-/truss-supported concepts due to the relative stiffness and strength of the latter shelters. The three rigid wall

[1]As with their small shelter counterparts, the air-supported fabric hangar (concept 5) is dominated by the air beam fabric hangar (concept 3). Therefore, although the results for concept 5 are shown for completeness, we will generally omit the air-supported fabric concept from our discussion of large shelter results since it always ranks below the air beam concept.

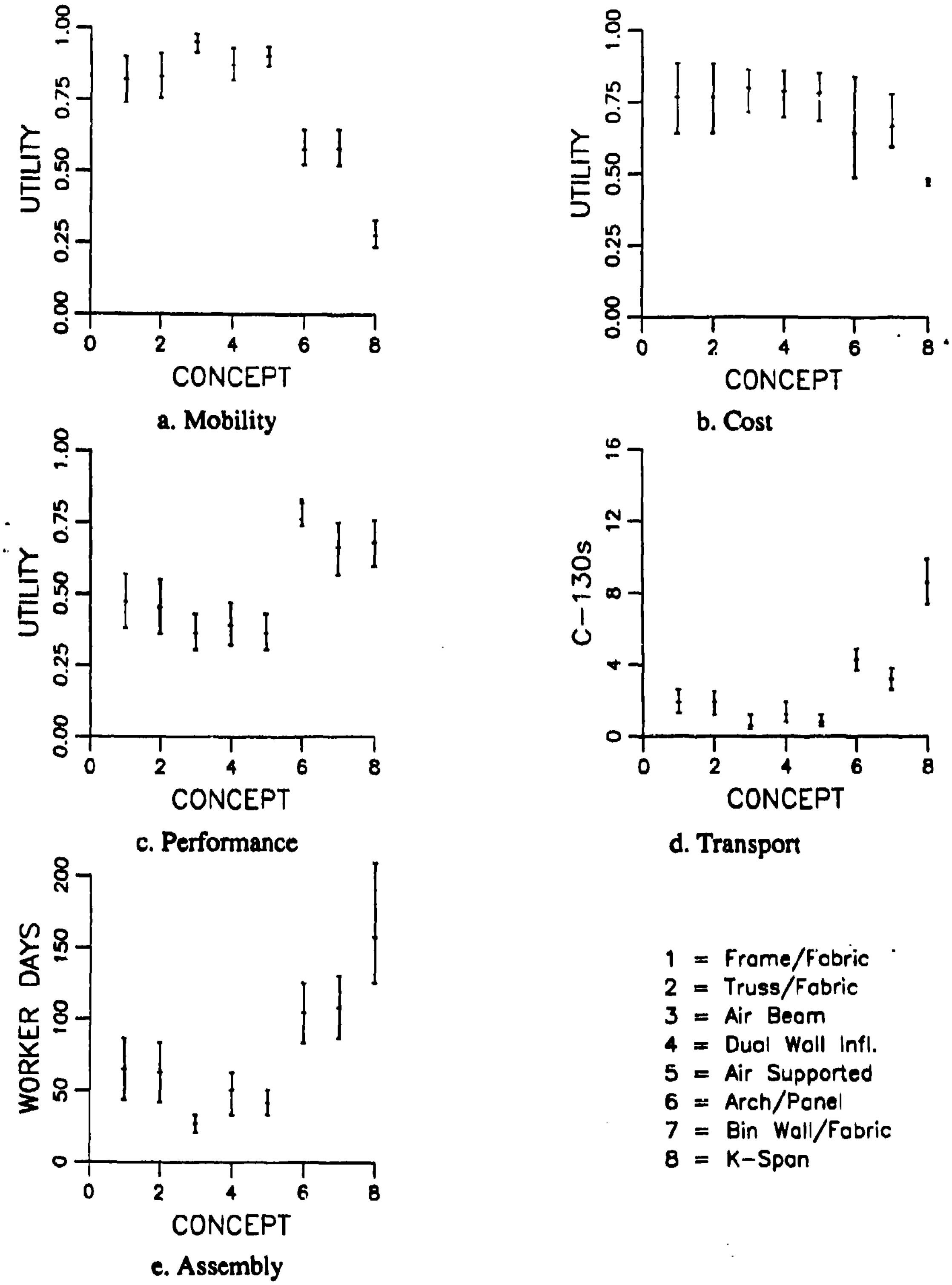


Figure 116. Basic Large Shelter Mobility, Cost, and Performance Results.

hangars provide the best basic shelter performance. The arch/panel concept is the overall leader due to its complete rigid panel enclosure and its higher expected thermal insulation compared to the corrugated steel K-Span concept.

b. Mobility, Cost, Performance, and Survivability — Basic and Upgraded Concepts *(Figure 117)*

With the exception of the bin wall hangar concept, none of the basic portable hangar concepts offers a substantial level of fragment protection. The arch/panel and K-Span shelters provide minimal fragment protection in their basic configurations, and the fabric shelters offer virtually no protection. Therefore, we once again consider the four hardening upgrades described in Section IV.D.2. The relative impacts of the soil, aluminum panel, S2-glass panel, and Spectra® blanket upgrades on the four first-level objectives in the ASEM hierarchy are shown in Figure 117.

The utilities of the hardening upgrades with respect to the survivability objective are essentially the same as for the small shelter concepts. However, over the area of a large shelter wall (80 *feet* long with a 15-*foot* vertical projection), the average angle of incidence for striking fragments will be higher, some of the fragments will strike at slower velocities (due to longer slant ranges), and the density of fragment hits will be lower if portions of the wall lie outside of the threat weapon's beam spray. Therefore, slightly lower perforation densities are generally expected over the exposed area of the large shelter walls. In addition, the inclination of the lower panels on the arch/panel concept cause higher angles of incidence and further reduce the perforation density. The resulting survivability utilities for the cluster munition threat at a standoff of 100 *feet* are shown in Figure 117.d.

The mobility and cost objectives are both degraded by the installation of the hardening upgrades. Again, fabric shelters suffer the largest reductions in mobility and cost utility since they start at the highest levels. However, since the vertical wall area of the large shelters represents a smaller portion of the overall surface area than in the small shelter, the relative impacts of the hardening upgrades on the mobility and cost attributes of the portable hangars are less severe than in the small shelters. As with the small shelters, Spectra® blankets are the best hardening method in terms of mobility but the least desirable in terms of cost. The S2-glass panel upgraded arch/panel shelter and the increased soil thickness upgrade for the bin wall shelter are competitive with the panel or soil hardened air-inflated fabric shelter concepts, which require free-standing hardening upgrades. However, as with the small shelters, the rigid wall portable hangar concepts must primarily rely on survivability and basic shelter performance to offset their lower cost and mobility utilities.

For the large shelter concepts, we have assumed that basic shelter performance is not changed by the application of hardening upgrades. Since panel upgrades on frame-supported fabric shelters cover a relatively small portion of the total shelter surface area,

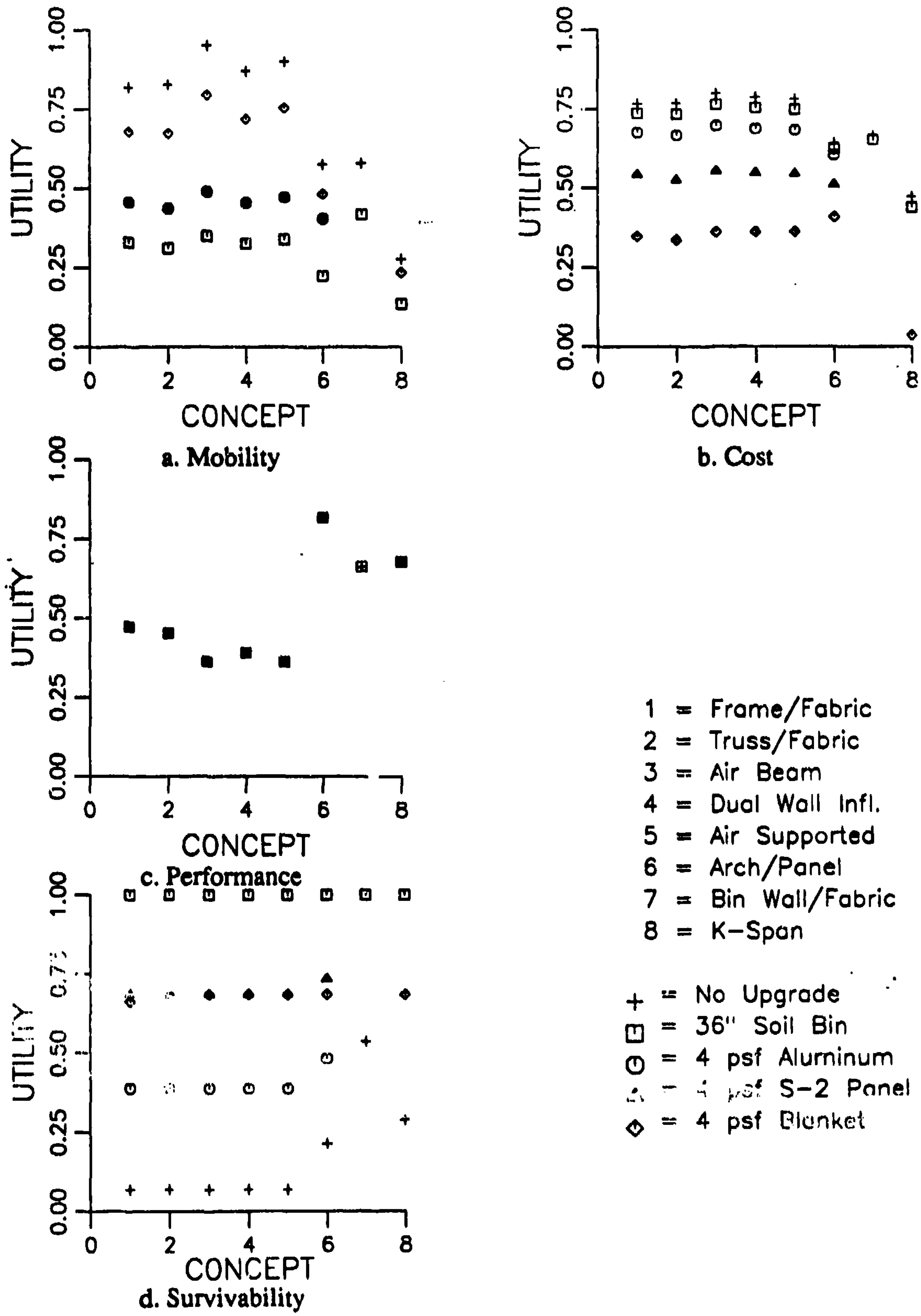


Figure 117. First-Level Results for Basic and Upgraded Large Shelter Concepts.

we did not increase the average R-Values of these shelters. As with the small shelter concepts, we can conclude that basic shelter performance is not likely to be degraded by the application of hardening upgrades.

c. Overall Utility — Basic and Upgraded Concepts (*Figure 118*)

The overall utilities of the eight basic and upgraded portable hangar concepts are shown in Figure 118. Under three of the four preference sets used in the ASEM studies, the basic and upgraded arch/panel and bin wall hangars are consistently ranked as the leading concepts. The No-Survivability preference set is the only case under which the arch/panel and bin wall concepts do not rate the best. When survivability is given little or no priority, the basic air beam and frame-supported fabric shelter concepts excel. However, even under the No-Survivability preference set, the basic arch/panel and bin wall hangar concepts are competitive with the fabric hangar concepts. For survivability scaling factors equal to or in excess of the preference levels inferred from the RWG survey, the basic and upgraded arch/panel and bin wall hangar concepts outperform the fabric hangar concepts.

For the arch/panel concept, the soil bin, S-2 panel, Spectra® blanket upgrade configuration utilities approximately meet or exceed the overall utilities of the basic, unhardened concept. For the bin wall concept, the only upgrade considered is an increase wall thickness with 36 *inches* of soil infill. The overall utility of the upgraded bin wall concept is also similar to or better than that of the basic bin wall concept (which has 12 *inches* of soil). In both cases, the relative utilities of the hardening upgrades improve as the importance placed on survivability is increased.

The bin wall hangar is an unproven design concept. Therefore, the utility of the concept will ultimately depend on whether our estimates for its design attributes can actually be met in practice. Detailed design studies on the structural feasibility of the bin wall concept will be required in the next phase of the FOPS development program. Some specific issues include: lateral stability under wind and blast loads, hangar deployment without the use of soil to fill-in the bin walls, wall/roof connections, packaging concepts, and rapid assembly concepts.

Since there is a possibility that minimum mobility and cost thresholds will be set for the FOPS hangar that cannot be met by the arch/panel or bin wall concepts, the basic air beam hangar concept should also be pursued as a high payoff concept for shelter mobility and cost. As with the small shelter concepts, the frame-supported fabric hangar represents a balanced, low risk back-up alternative to the air beam hangar concept.

F. SENSITIVITY ANALYSIS

The relative priorities assigned to survivability and mobility and the single attribute utility functions used to characterize packing ratio and perforation density are the key parameters

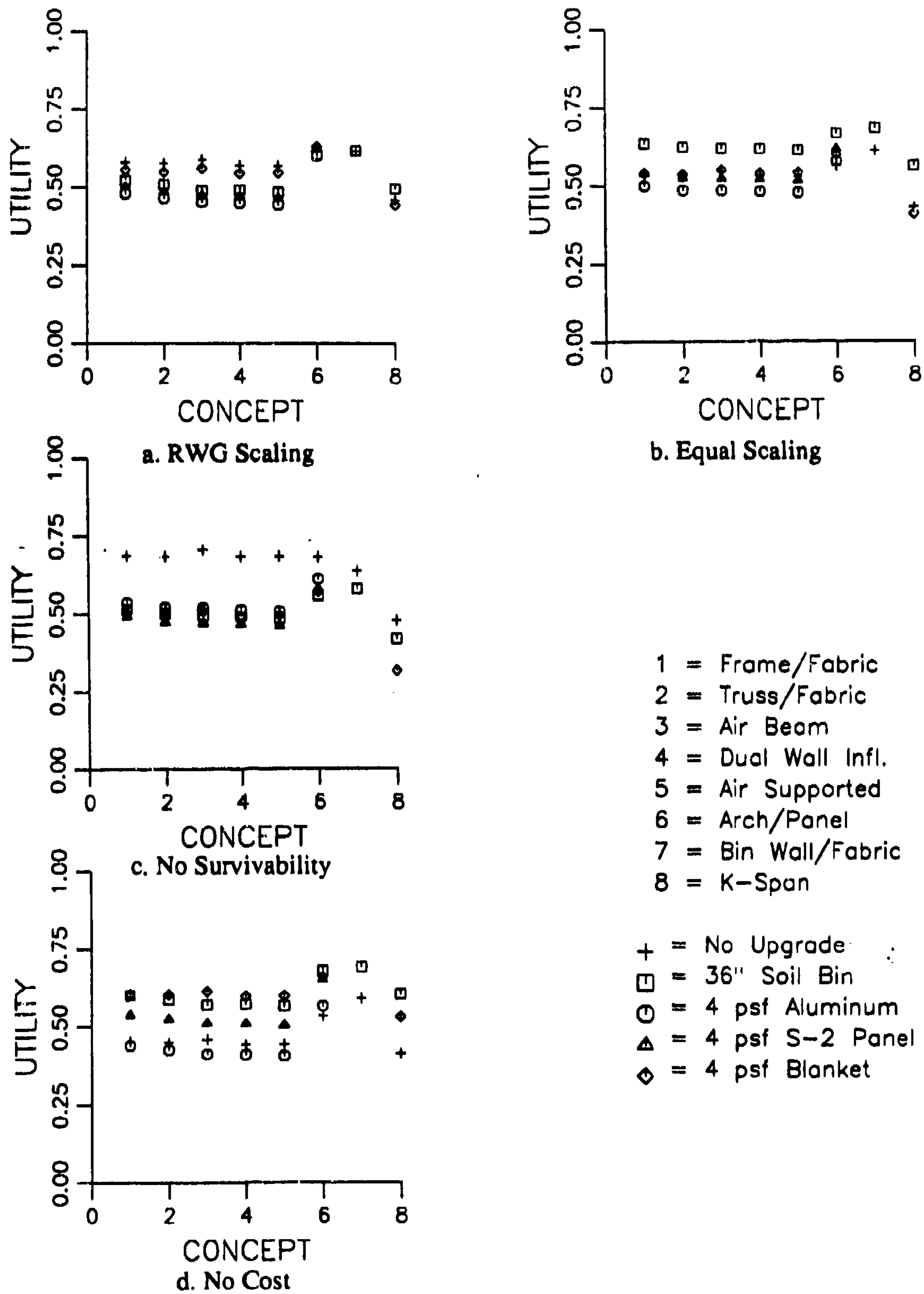


Figure 118. Overall Large Shelter Results.

that affect the selection of preferred design concepts. In this section, we examine the sensitivity of the overall utilities of the leading shelter concepts to variations in these parameters.

1. Sensitivity to Survivability Priority

Under the current ASEM model, the survivability scaling constant should reflect the importance AF decision makers place on reducing the number of fragment perforations for the cluster munition threat at a standoff of 100 *feet*. That is, the priority placed on the survivability attribute should be based on the fragment protection levels provided against this specific threat, and it should be judged relative to the importance of increasing the specific mobility, cost, and basic shelter performance attributes. As we stated in Section IV.C.3, the preference sets used in the ASEM studies were not generated by direct interaction with designated AF decision makers. Rather, the preference sets are based on a combination of indirect factors: the RWG meeting and survey results, the ORD thresholds and objectives, our technology review, and our general interactions with members of the portable shelter user and research communities. Therefore, given the importance of the survivability scaling factor (k_s) as well as the uncertainties and subjectivities associated with its estimation, it is important to understand the sensitivity of the preferred shelter concepts to various values of k_s.

a. Small Shelter Sensitivity to k_s

We have selected six leading small shelter design concepts for the survivability sensitivity studies: (1) the basic air beam fabric shelter, (2) the basic airmobile MERWS shelter, (3) the MERWS with 36-*inch* soil bins, (4) the MERWS with S2-glass panels, (5) the MERWS with Spectra® blankets, and (6) the upgraded 36-*inch* block wall shelter. Figure 119 shows two plots of overall utility as a function of k_s. In Figure 119.a, the mobility, cost, and performance, scaling constants, (k_m, k_c, and k_s, respectively) are assumed to be equal. That is,

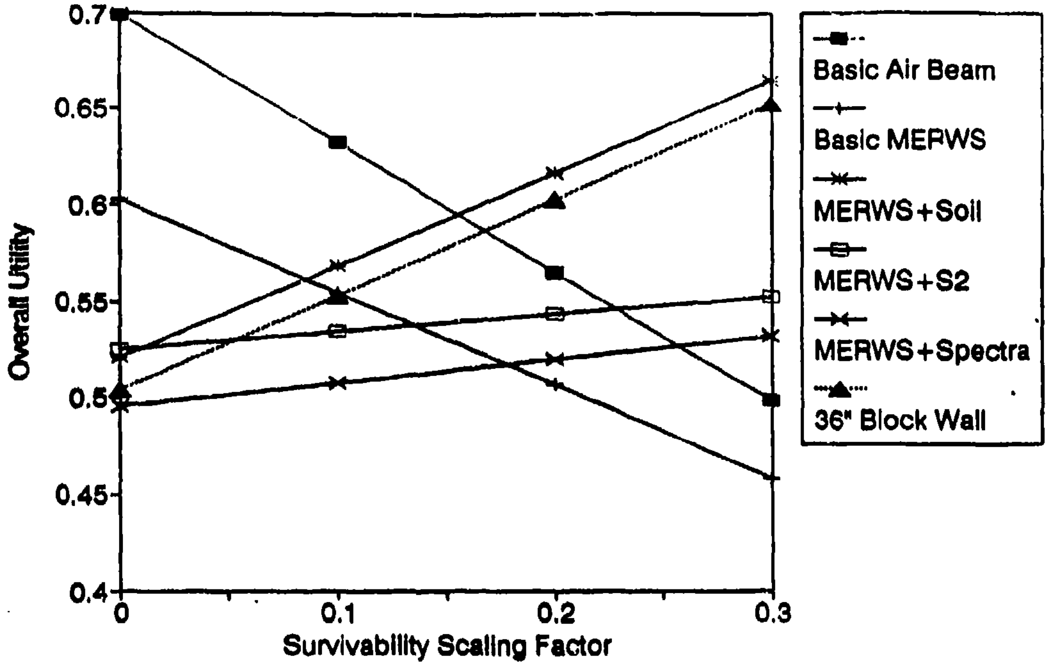
$$k_m = k_c = k_p = (1 - k_s)/3 \tag{26}$$

When $k_s = 0.25$, all four constants are equal and the Equal scaling preference set results. In Figure 119.b, the four scaling constants are in the approximate proportions used in the RWG preference set:

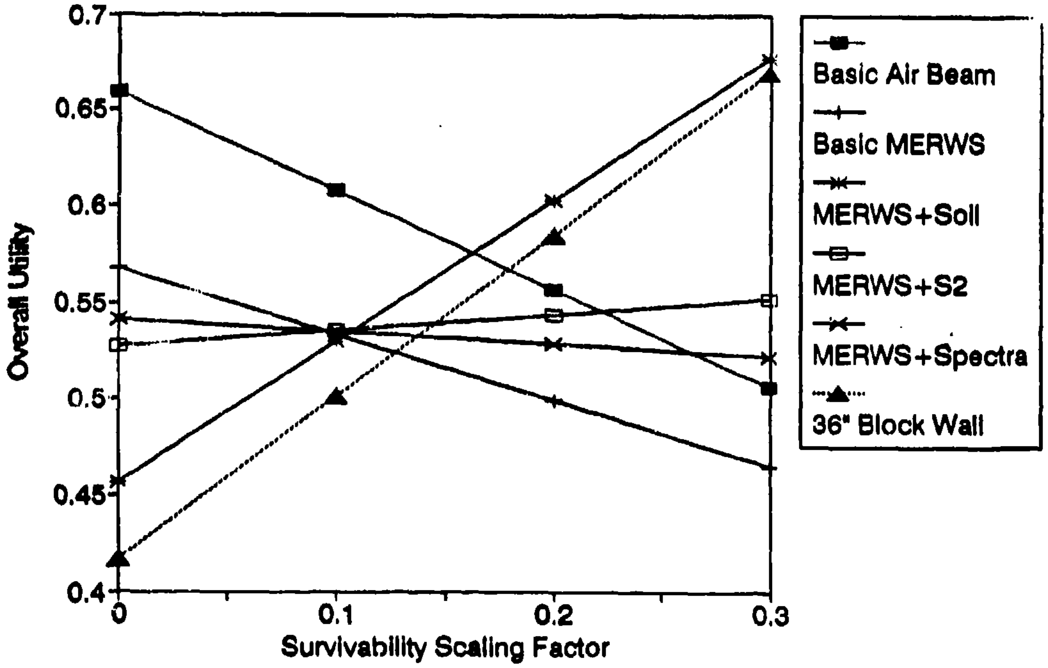
$$\begin{aligned} k_m = k_p &= (1 - 2\,k_s)/2 \\ k_c &= k_s \end{aligned} \tag{27}$$

When $k_s = k_c = 0.125$ and $k_m = k_p = 0.375$, these values closely approximate the RWG scaling set.

Under both families of preference sets, the upper envelopes in Figures 119.a and 119.b are quite similar. The basic air beam concept controls up to $k_s = 0.15$, but beyond this point the soil-hardened airmobile MERWS concept takes over as the leading



a. Equal Scaling



b. RWG Scaling

Figure 119. Small Shelter Sensitivity to Survivability Scaling Factor.

concept. If we interpret the RWG survey results as an indicator of the importance of hardening portable shelters against anti-personnel weapon fragmentation effects (a significant assumption), k_S is approximately 0.13, and the two leading concepts have nearly identical utilities. More importantly, however, we note that a stronger preference either for or against survivability will result in higher overall utility. In other words, if a strong consensus on the question of survivability preferences can be achieved, overall shelter utility is likely to improve.

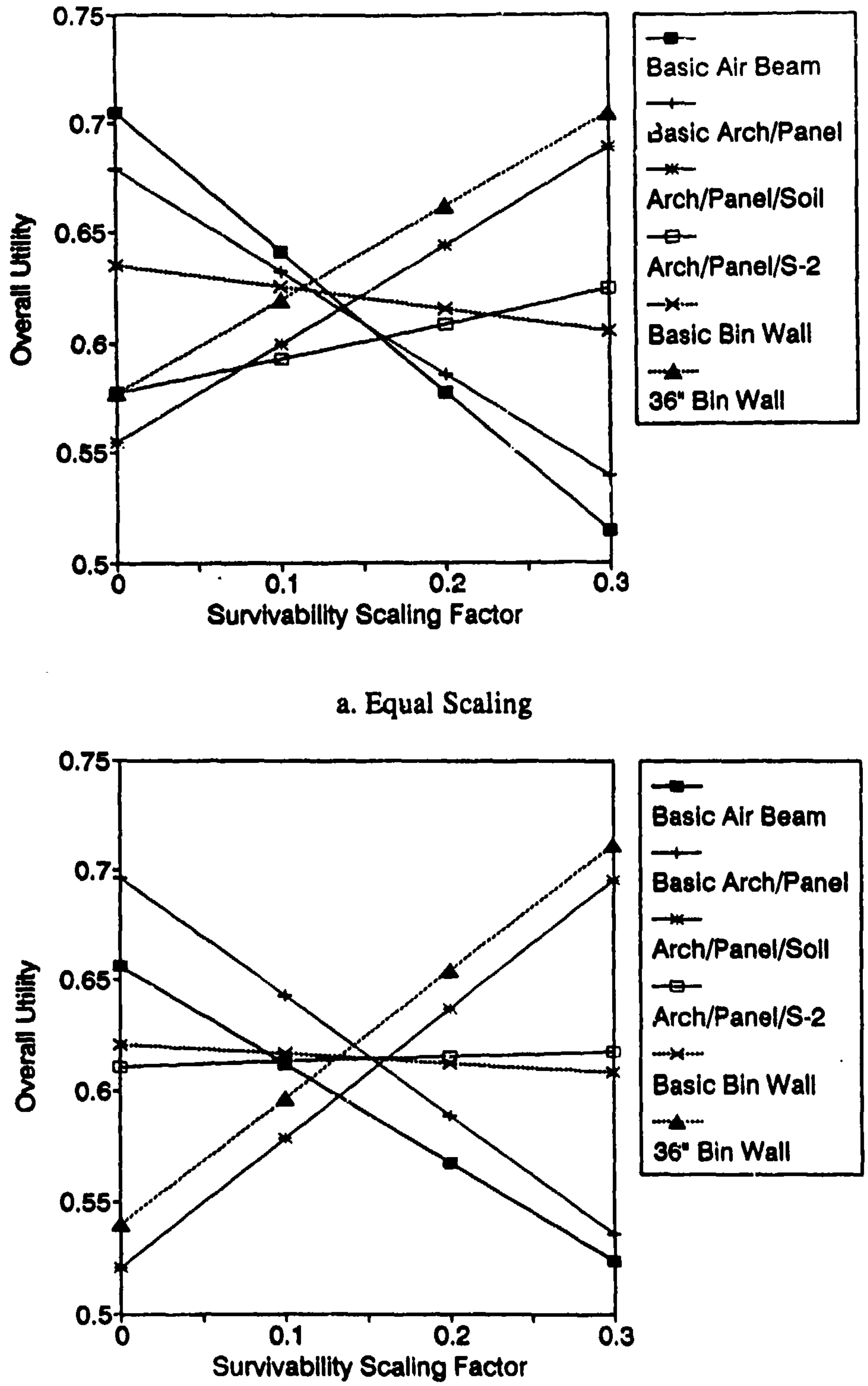
Among the other leading small shelter concepts, the 36-*inch* block wall concept falls just below the soil-hardened MERWS over the entire range of k_S in both plots, and the basic MERWS concept parallels the trend of the basic air beam shelter. The separation in overall utilities is much more significant for the latter pair of concepts than it is for the former (particularly at low values of k_S).

For both preference sets, the overall utilities of the S2 panel and Spectra® blanket hardened MERWS concepts remain relatively constant throughout a wide range of k_S. This insensitivity implies that the S2 and Spectra® upgrades offer a relatively equal trade-off between survivability and the other first-level design objectives. Under the RWG family of preference sets, a crossover point between the S2 and Spectra® upgrades occurs at $k_S = 0.10$. The crossover occurs because k_C is directly tied to k_S in Figure 119.b. Thus, as k_S increases, the lower cost of the S2 panels compared to the Spectra® blankets becomes the critical factor. If soil-based hardening methods are not feasible, the S2 and Spectra® upgrades become the leading hardening approaches. However, the S2 and Spectra® hardened MERWS concepts are not preferred to the basic air beam concept until k_S reaches values of 0.22 to 0.26. This observation holds for both the Equal and RWG preference families. Thus, a strong preference for survivability is required to justify S2 or Spectra® upgrades over the entire wall area. A selectively hardened shelter (see Section III.G.4), however, would require less sacrifices in terms of cost and mobility. Therefore, selective hardening would move the crossover point to lower values of k_S.

b. Large Shelter Sensitivity to k_S

For the large shelters, we have also selected six leading design concepts for the survivability sensitivity studies: (1) the basic air beam fabric hangar, (2) the basic arch-supported panel hangar, (3) the arch/panel with 36-*inch* soil bins, (4) the arch-supported hangar with S2-glass panels on the lower fifteen *feet*, (5) the basic 12-*inch* bin wall hangar, and (6) the upgraded 36-*inch* block wall shelter. Figure 120 shows plots of overall utility as a function of k_S. The same two families of preference sets are used for the large shelter sensitivity studies as were used in the previous subsection for the leading small shelter concepts.

At low values of k_S, the leading concept under Equal scaling is the basic air beam shelter, but under RWG scaling the basic arch/panel concept is most preferred. The difference is due to the lower emphasis on cost and higher emphasis on basic performance in the RWG family of preference sets. At k_S values above 0.12 to 0.14, the 36-*inch* bin wall concept



a. Equal Scaling

b. RWG Scaling

Figure 120. Large Shelter Sensitivity to Survivability Scaling Factor.

ranks first under both scaling sets. The bin-wall concept is paralleled by the soil-hardened arch panel concept under both scaling sets. As with the small shelters, the mid-range values of k_s correspond to the lowest points of the large shelter overall utility envelope. Thus, an increase or decrease in k_s will produce a leading concept with better overall utility.

The intermediately hardened large shelter concepts (*i.e.*, the 12-*inch* bin wall and the arch-supported S2 panel shelter) are fairly insensitive to the survivability scaling factor under both preference sets. This insensitivity implies that the 12-*inch* bin wall and S2 panels offer a relatively equal trade-off between survivability and the other first-level design objectives. Crossover points between the S2 and 12-*inch* soil hardening methods occur at k_s values 0.15 to 0.22. The S2 panels become preferred as k_s increases due to the lower perforation density in the 4 *psf* S2 panels (see Table 38). For the large shelter concepts, the arch-supported S2 panel shelter becomes preferred to the basic arch/panel hangar and the basic air beam hangar at k_s values greater than 0.10 to 0.15.

2. Sensitivity to Single Attribute Utility Function Curvature

As with the overall preference sets, the single attribute (or marginal) utility functions presented in Section C.2 were not developed by direct interaction with designated AF decision makers. Rather, the best, worst, and median values used to characterized the marginal utility functions reflect our estimation of AF preferences with respect to each individual design attribute. Due to their large scaling factors and wide ranges of possible outcomes, packing ratio and fragment perforation density play particularly important roles in determining the preferred shelter concepts. Therefore, we assess the sensitivity of the overall utilities of the leading small and large shelter concepts to the packing ratio and perforation density utility functions in this section.

The sensitivities of the overall shelter utilities to the packing ratio and perforation density utility functions are evaluated through perturbations of the median attribute values. Recall that the median value of the i^{th} attribute is the value, x_i, that corresponds to marginal utility of 0.50 (*i.e.*, $u_i(x_i) = 0.50$). Perturbing the median value changes the degree of curvature in the single attribute utility functions shown previously in Figures 112.a and 112.1. The specific perturbations on median packing ratio and perforation density that we apply to the packing ratio and perforation density utility functions are discussed in the following two subsections. We have selected ten leading small shelter concepts and ten leading large shelter concepts for the sensitivity studies. The selected shelters are summarized in Table 39. Both the RWG and Equal preference sets are considered in the sensitivity studies.

a. Sensitivity to Median Packing Ratio

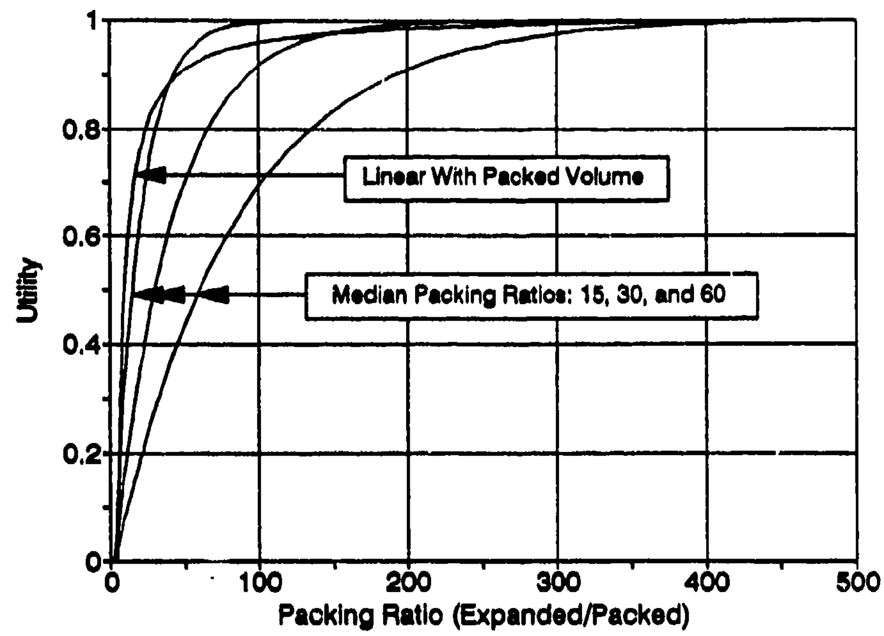
The affects of three different packing ratio utility functions on overall shelter utility are evaluated in this section. Figure 121.a illustrates three exponential utility functions with packing ratios ranging from 3 to 500 and median values of 15, 30, and 60,

TABLE 39. SHELTER CONCEPTS CONSIDERED IN THE SINGLE ATTRIBUTE UTILITY FUNCTION SENSITIVITY STUDIES.

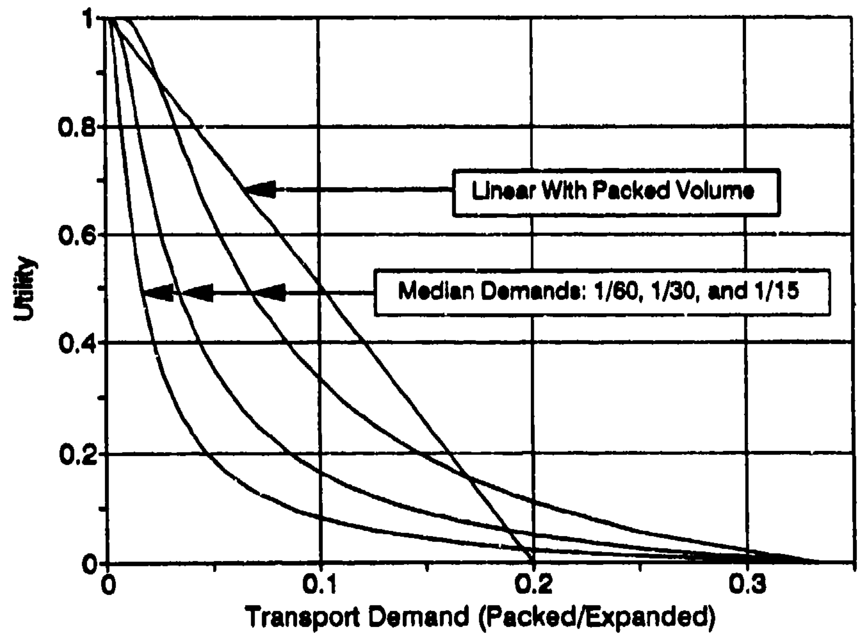
Size	Type	Configuration/Upgrade	Symbol
Small	Frame-supported fabric	Basic	2BS
		S2-glass panels	2S2
	Air beam fabric	Basic	4BS
		Soil bins	4SL
	Airmobile MERWS	Basic	8BS
		Soil bins	8SL
		S2-glass panels	8S2
		Spectra® blankets	8SP
	Block wall	36-*inch* soil wall	11SL
	Reinforced earth	Basic	13BS
Large	Frame-supported fabric	Basic	1BS
		S2-glass panels	1S2
	Air beam fabric	Basic	3BS
		Soil bins	3SL
	Arch-supported panel	Basic	6BS
		Soil bins	6SL
		S2-glass panels	6S2
		Spectra® blankets	6SP
	Bin-wall	Basic, 12-*inch* soil wall	7BS
		36-*inch* soil wall	7SL

respectively. Until now, the only packing ratio utility function that we have used is the curve with a median value of 30. Thus, we will investigate the impact of shifting the median packing ratio by a factor of two above and below the base case.

We also show a fourth possible utility function in Figure 121.a. This function is linear with respect to packed volume (*i.e.*, linear in the inverse of packing ratio — see Figure 121.b). Since the required number of transport planes is directly proportional to packed volume, we refer to the curves shown in Figure 121.b as transport demand utility functions. The implication of a linear transport demand utility function is that equal value is attached to every transport plane, regardless of how many or how few may be required. Therefore, under a linear transport demand utility function, the incremental gain in utility when packing ratio is increased from 10 to 12.5 is the same as gain achieved by increasing packing ratio from 25 to 50 since, in both cases, transport demand is reduced by 0.02 *feet*^{3} of packed volume per *foot*^{3} of expanded usable volume. The magnitude of the incremental utility gain depends entirely upon range of possible transport demands which, in turn, is primarily determined by the transport demand that corresponds to zero utility.



a. Packing Ratio



b. Transport Demand

Figure 121. Packing Ratio and Transport Demand Utility Functions.

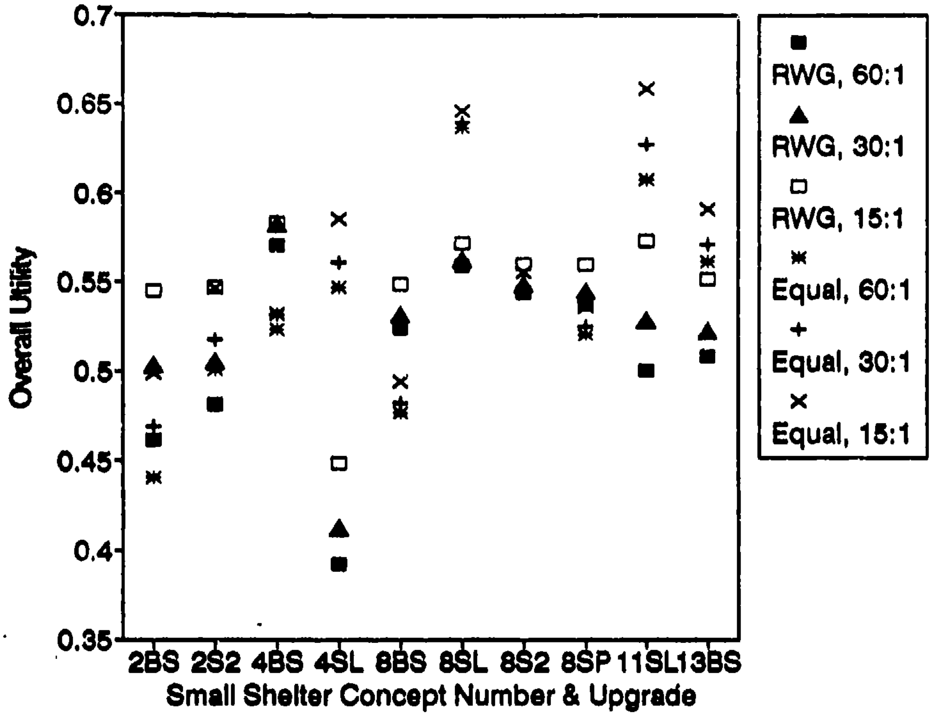
Our purposes in introducing the linear transport demand utility function are to explain the necessity for a relatively sharp curvature in the packing ratio utility function and to provide a more meaningful interpretation of the relative benefits of increased packing ratio. Since the current version of ASEM was not designed to accommodate a linear transport demand utility function, we can only approximate its affect on overall shelter utility in the present sensitivity study. Of the three utility functions considered in this sensitivity study, the packing ratio utility function with a median value of 15 most closely approximates the linear transport demand utility function (for packing ratios ranging from 5 to 500).

Figure 122 summarizes the results of the packing ratio utility function sensitivity study. The median values and preference sets associated with each point shown in Figure 122 are displayed in the figure legends, and the symbols used to identify the shelter concepts are summarized in Table 39.

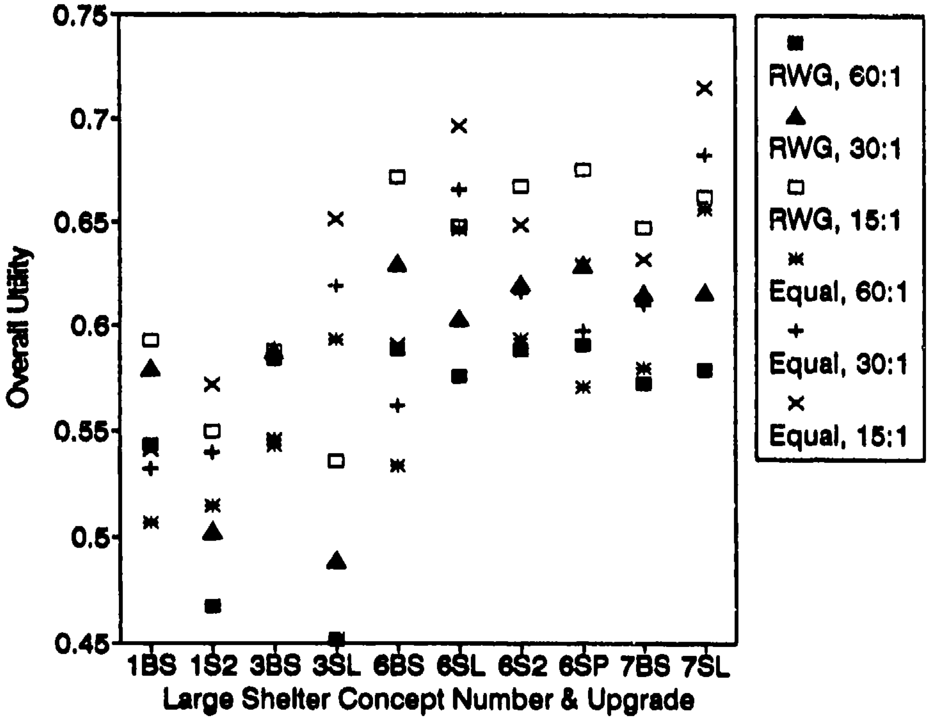
For both the small and large shelter concepts, we note that within a given preference set (*i.e.*, RWG or Equal) overall shelter utility always increases as the median packing ratio is decreased. The affect of median packing ratio on overall utility is slightly greater under RWG scaling than under Equal scaling because mobility receives greater preference under RWG scaling. The concepts least influenced by changes in median packing ratio are those at the two ends of the spectrum (*i.e.*, the hardened MERWS small shelter concepts and the basic air beam small and large shelter concepts). The shelters most heavily influenced by median packing ratio are those having packing ratios near 30. Many of the upgraded fabric hangars and basic or upgraded rigid wall hangars fall in this critical region, and, in some of these cases, the changes in overall utility approach 0.10 as median packing ratio is decreased from 60 to 15.

Under RWG scaling, the top three or four small and large concepts are basically unchanged by the variations in median packing ratio. For the small shelters, the only exception is the upgraded block wall concept which rises from sixth place to second place when the median packing ratio is reduced from 30 to 15. Among the top three large shelter concepts, the arch/panel with Spectra® blanket upgrades moves from second place to first place (replacing the basic arch/panel concept) when the median packing ratio is increased from 30 to 60 and when it is decreased from 30 to 15. We must point out, however, that the overall scores of the two shelters are virtually identical for each of the three median packing ratios. Therefore, although these results for the two leading RWG large shelters are somewhat surprising, the differences between their overall utilities are not significant.

For the Equal scaling preference set, the relative positions of the top small and large shelter concepts are also relatively insensitive to median packing ratio. Among the small shelters, the exception once again is the block wall concept, which benefits significantly when median packing ratio is reduced from 30 to 15. This change pushes the upgraded block wall ahead of the soil hardened MERWS and into first place. There are no changes in the rankings of the three top large shelter concepts under Equal scaling when median packing ratio is varied.



a. Small Shelter



b. Large Shelters

Figure 122. Sensitivities of Leading Overall Shelter Concepts to Median Packing Ratio.

In summary, an increase in med..n packing ratio improves the relative standing of shelters with extreme packing ratios (since the utilities of the intermediate shelters decline), while a decrease in median packing ratio improves the relative standing of the shelters with intermediate packing ratios. The latter case also approximates the affect of changing from the current baseline packing ratio utility function to a linear transport demand utility function.

b. Sensitivity to Median Perforation Density

Next, we investigate the affects of three different perforation density utility functions on overall shelter utility. Figure 123 illustrates three exponential utility functions ranging from perforation densities of 0.0 to 1.0 perforations per 10 *feet*^{2}. The median values of the three utility function are 0.2, 0.1, and 0.05. To generate the basic ASEM results presented in Section E, we used the perforation density utility function with a median value of 0.2. Thus, we now assess the impact of reducing median packing ratio by a factor of two or four on the overall utilities of the leading small and large shelter concepts. The reductions can be interpreted as means of imposing stricter survivability performance requirements on the candidate shelter concepts. That is, we are requiring lower perforation densities to achieve a given level of survivability utility.

Figure 124 summarizes the results of the perforation density utility function sensitivity study. The median values and preference sets associated with the overall utilities shown in Figure 124 are displayed in the figure legends. We have selected the same leading shelter concepts used in the packing ratio sensitivity analysis for the perforation density sensitivity study. The symbols used to identify the selected shelter concepts are summarized in Table 39.

Within a given preference set (*i.e.*, RWG or Equal), overall shelter utility always decreases as the median perforation density is decreased. The affect of median perforation density on overall utility is slightly greater under Equal scaling than under RWG scaling because survivability receives greater preference under Equal scaling. Shelters with 36 *inches* of soil protection are unaffected by the changes in the median value because their perforation density is zero (*i.e.*, a survivability utility of 1.0). Similarly, unprotected shelters are also essentially unaffected by changes in the median perforation density because they already have perforation densities near 1.0 (*i.e.*, a survivability utility of essentially 0.0). Shelters influenced by variations in median perforation density include those with aluminum, S2-glass, Spectra®, or 12 *inches* of soil in either their basic or upgraded configurations. Thus, only four of the ten leading small shelter concepts and five of the ten leading large shelter concepts are influenced by the reductions in median perforation density.

Under RWG scaling, significant changes occur in the top three small and large concepts as median perforation density is reduced. For the small shelters, the S2-glass hardened MERWS concept falls from third to fifth to seventh place as the median value is reduced from 0.2 to 0.1 to 0.05, respectively. Thus, the value of the 4 *psf* S2-glass panel upgrade

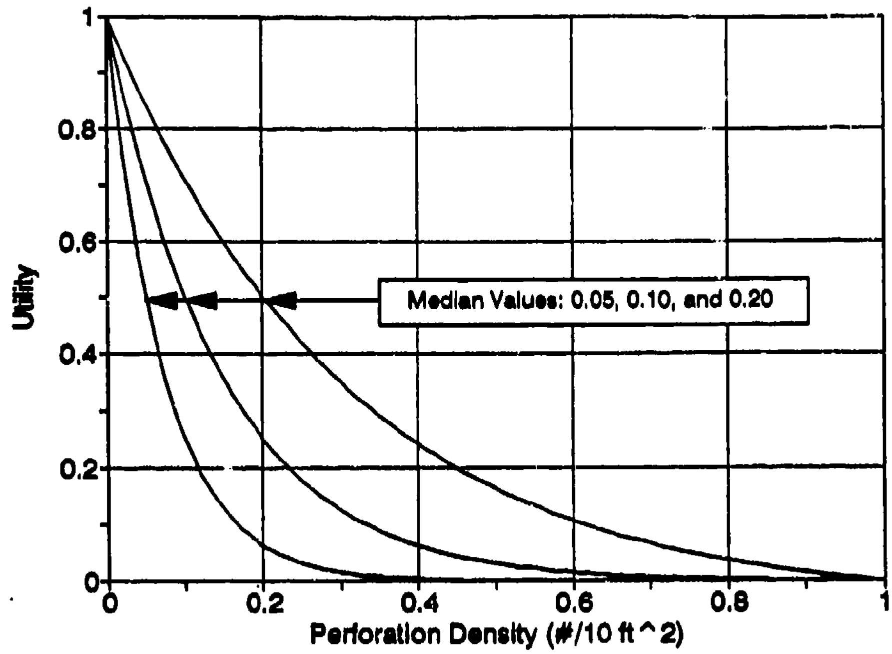
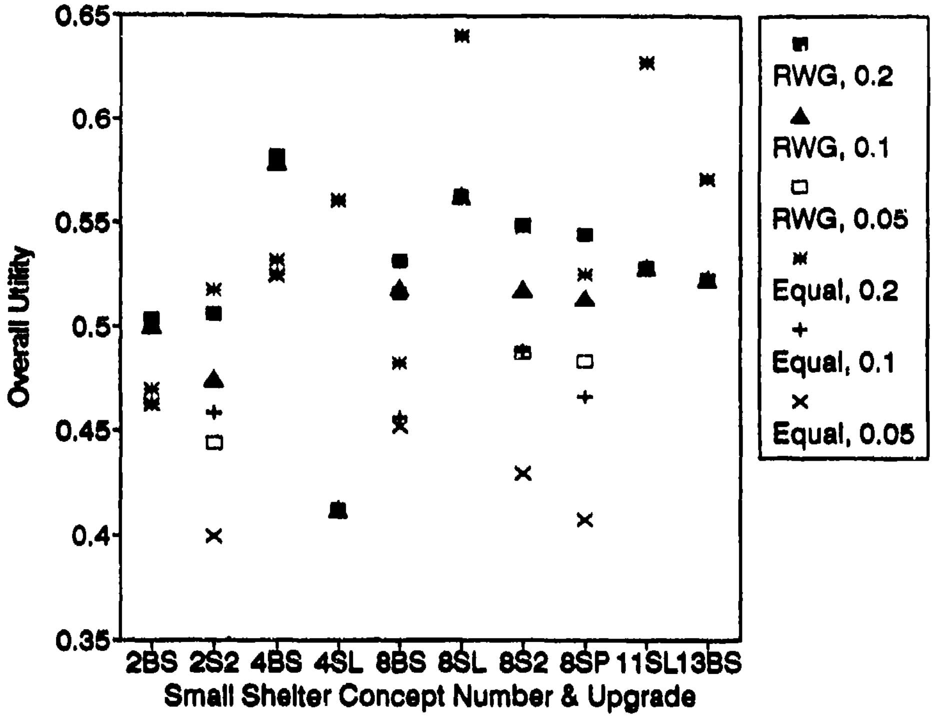


Figure 123. Perforation Density Utility Functions.

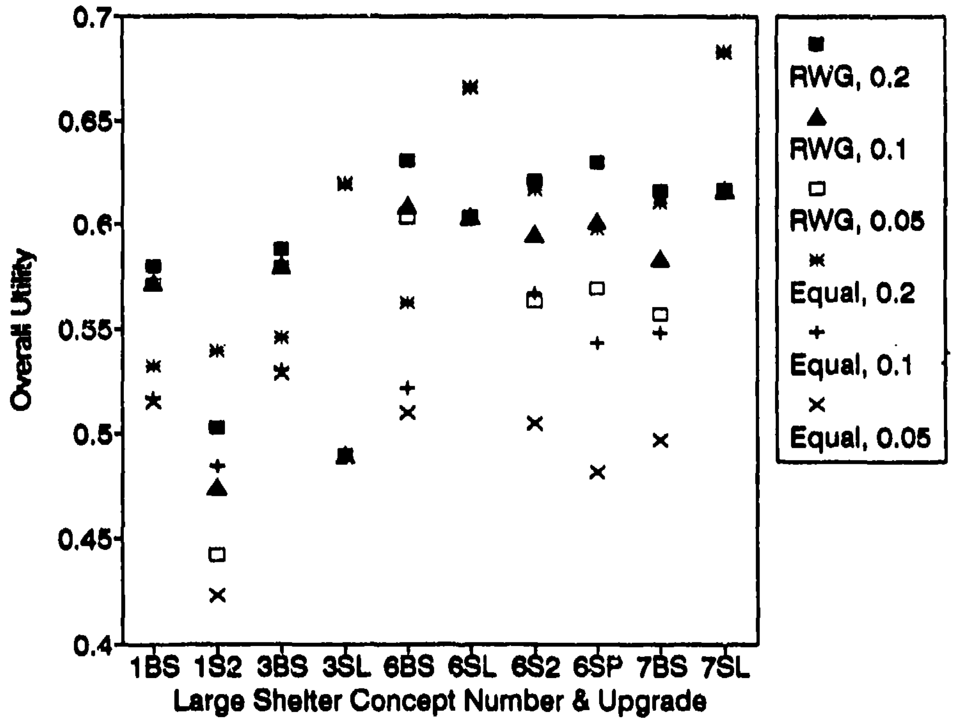
when exposed to the cluster munition at a standoff of 100 feet depends heavily on the precise definition of acceptable survivability. The S2-glass hardened MERWS is replaced by the 36 inch block wall shelter as the third rated small shelter concept. This concept is insensitive to the curvature of the perforation density utility function. Interestingly, the top thre concepts under the most restrictive perforation density utility curve consist of one highly mobile, unprotected shelter (the basic air beam shelter) and two low mobility, high survivability shelters (the soil-hardened MERWS and block wall concepts).

Among the top three RWG large shelter concepts, severa changes occur as the median value is reduced. The 36-*inch* bin wall hangar rises from fourth o first and the basic arch/panel hangar drops from first to second when the median perforation density is below 0.2. Like the bin wall concept, the soil hardened arch/panel shelter maintains its overall utility and becomes one of the top three large shelter concepts as the median value is reduced.

For the Equal scaling preference set, the top small and large shelter concepts are all soil hardened and, as a result, are completely insensitive to median perforation density. As in the RWG case, the S2-glass hardened MERWS and arch/panel concepts rate fairly well when the median value is 0.2 (fourth place for the small and large shelters, respectively), but they drop off quickly as the median perforation density is reduced.



a. Small Shelter



b. Large Shelters

Figure 124. Sensitivity of Leading Overall Shelter Concepts to Median Perforation Density.

In general, a sharper degree of curvature (*i.e.*, decreasing median perforation density) significantly affects the overall utility of the intermediately hardened shelters concepts. Thus, the preferred shelter concepts can be very sensitive to the specification of the design threats and threshold probabilities of survival. A push for high confidence survivability may tend to eliminate lightweight composites in favor of either soil-based hardening upgrades or no upgrades at all. This issue should be addressed by AF decision makers early in the next phase of the FOPS development program.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. Hardening

A major goal for the new FOPS is to provide protection against the blast and fragmentation effects of conventional munitions. The SON and ORD specify Splinter Protection as the minimum protection level with Semihardened as a goal for high value targets. The basic assumption behind specifying these protection levels for FOPS is that they may be achievable through the use of modern ballistic composites, such as Kevlar®, Spectra®, and S2-glass.

Section III presents our assessment of the hardening feasibility for FOPS. To perform this assessment, we developed the SAFE code. SAFE accurately describes the fragmentation characteristics for the munition and maps fragment impacts and perforation response over the target surface. The munition surface is discretized into cells which are projected onto the shelter walls using straight line trajectories. For each munition cell, the critical fragment weight and velocity causing perforation of the shelter wall is determined. Combined with the fragment weight distribution for the munition, these quantities provide the expected number of perforations. The average number of perforations over the shelter surface is used as one of the design attributes in the ASEM shelter evaluation model.

Our assessment considered a range of weapon types and potential hardening upgrades. Based on the Splinter Protected and Semihardened threat definitions specified in the SON and ORD, and a review of airbase threat documents, we selected and developed SAFE fragmentation models for six representative weapons: (1) a 1000-*pound* bomb, (2) a 40-*mm* A/C cannon, (3) a cluster munition, (4) a 152/155-*mm* artillery round, (5) a 122-*mm* rocket, and (6) a 250-*pound* missile. Section III and Appendix G summarize the fragmentation characteristics for these munitions. Weapon standoffs, materials, and wall thicknesses were varied to determine the weight and cost penalties for hardening with modern composites. For large standoffs and light protection levels, fragmentation is the controlling weapon effect; however, as additional mass is added to the shelter walls and weapon standoffs are reduced, airblast becomes increasingly important and may be the controlling weapon effect for some munitions.

The hardening upgrades considered included ballistic fabrics, ballistically hardened panels, and soil covers. The first two hardening methods incorporate modern ballistic composites either as an integral part of the shelter (*i.e.*, the fabric shell or rigid panels) or as field installable upgrade kits (shields and liners). Soil covers include expedient hardening upgrades such as soil bins, sandbags, and soil berms. These hardening upgrades can also be integral (as in the case of the bin-wall and reinforced earth shelters proposed in Section II) or field expedient. Areal densities considered for the fabric and panel upgrades ranged from 1 to 8 *psf* (16 and 32 *psf* densities were calculated for selected cases) while soil thicknesses were varied from 1 to 4 *feet*.

Our results show that only the soil bin walls and soil berms are capable providing Splinter level protection at low costs. While significant hardness levels can be achieved by incorporating modern ballistic composites such as Kevlar®, Spectra®, and S2-glass, it is not feasible to harden the entire shelter to Splinter levels of protection, as discussed in Appendix H. The three composite materials (fabric or panel) all provided comparable levels of protection, but were not capable of stopping the large, high-speed fragments generated by the 1000-*pound* bomb and 250-*pound* missile at realistic areal densities. Appendix H shows that Splinter Protection can be provided for the 40-*mm* A/C cannon and 122-*mm* rocket at reasonable areal densities, but that areal densities required for the 250-*pound* missile and *1000-pound* bomb are excessive. These results emphasize the varying severity of the four weapon types encompassed by Splinter Protection and the difficulty in achieving Splinter Protection for the large munitions.

At present, the performance of S2-glass with HJ1 phenolic resin slightly lags behind that predicted for Kevlar® KM2 and Spectra®; however, THOR models for the latter two materials are based on smaller caliber FSPs and low areal densities. Ballistic testing with large caliber FSPs and panels with large areal densities is required for model verification. S2-glass, because of its lower cost and smaller panel thicknesses is still an attractive alternative. All three composites are as effective as twice the areal density of aluminum.

The heavy panel weights required for ballistic protection will significantly degrade shelter transportability and erection times. Alternatives to integrally hardening the entire shelter are: (1) optional upgrade kits, (2) expedient on site hardening, and (3) selective hardening. Optional upgrade kits and expedient on site hardening provide the flexibility of hardening only those shelters (or deployments) exposed to significant risk. Selective hardening concentrates ballistic materials into dedicated "safe" areas that provide very high levels of protection. Section III results show that by concentrating ballistic composite materials into the lower 2 *feet* of a panel, "Splinter Protection" can be achieved. In practice, providing this "Splinter Protection" over the bottom 2 *feet* will require segmenting the panel height for handling and erection. Horizontal joints and quick connectors will have to be developed and a frame may be required.

In addition to the lateral threats provided by the six munitions, we also considered an overhead threat due to an incoming artillery shell detonated at a HOB over the shelter. For survival criteria of 1 perforation per 10 *feet*^{2}, 2 *psf* of S2/HJ1 are required for an HOB standoff of 50 *feet*. Reducing the HOB standoff to 40 *feet* requires approximately 4 *psf* and 30 *feet* requires approximately 8 *psf*. Horizontal misses on the long side (+20 *feet*) also result in a larger number of perforations as fragments are sprayed back towards the roof. In this case, the roof is vulnerable (*i.e.*, perforation density exceeds 1 per 10 *feet*^{2}) at HOBs between 15 *feet* and 50 *feet*. The critical case falls between these two cases.

We recommend that the basic shelter be hardened to provide integral Splinter-type protection for small fragmenting munitions and be designed to support field installable or expedient methods for larger weapons. Section III results show that small areal densities (*i.e.*, 2 to 3 *psf*) of composite material are effective in stopping fragments from antipersonnel munitions such as A/C cannon fire and cluster munitions and also provide protection from most small arms fire. These areal densities can be easily incorporated into the shelter design and we recommend that this level of protection be provided as an integral feature of the shelter design.

To resist airblast loads, the structural system must be capable of supporting the dynamic loads imparted via the shelter shell. The cladding system can be strengthened to resist impulsive loads using one or more of the following methods: (1) higher strength and/or more ductile materials; (2) heavier and/or more efficient structural shapes; (3) smaller effective spans; and (4) stronger, more ductile connections. Shelter concepts with modular load bearing panels, such as MERWS, do not employ a frame as part of the structural support system. These shelters must react loads through discrete connectors between panels and are susceptible to collapse by lateral side sway. This susceptibility to side sway limits the wind and airblast resistance of MERWS. Consequently, we recommend modifying the MERWS design to incorporate a frame structure to react the panel loads. This frame system can be constructed of separate components, or can be integrated into the panel design. Detailed transient dynamic response analyses will be required during the preliminary shelter prototype design phase.

2. Concept Synthesis and Evaluation

a. Concept Synthesis -- Basic Shelter Concepts

In Section II, we present sixteen basic small shelter concepts and eight large shelter concepts as possible design alternatives for the next generation of portable shelters. Table 40 recapitulates the candidate small and large shelter concepts. Due to structural, geometric, and/or air-transportation constraints, many of the small span shelter concepts cannot be considered as candidate portable hangar concepts.

Our concept development approach was to systematically identify a wide range of design alternatives for each of the major shelter subsystems (*i.e.*, geometry, structural system, cladding system, and hardening upgrades). Although we do propose hardening-related shelter design modifications for some of the design concepts (*i.e.*, hybrid panel/fabric claddings and soil-filled walls), most of the basic concepts listed in Table 40 are either currently in use or under development. The remaining concepts have either been published previously (*e.g.*, the stressed membrane shelter), or they are portable shelter adaptations of existing construction techniques (*e.g.*, the composite hypar shell, the block wall shelter, and bin wall shelter concepts). Therefore, we do not consider any of the concepts listed in Table 40 to be entirely new or innovative.

b. Concept Development -- Hardening Upgrades

Based on the results of the SAFE hardening trade studies presented in Section III, we developed a standard set of four hardening methods as candidate upgrades for the small and large shelter concepts. The upgrade methods for the shelter evaluation studies were

TABLE 40. SUMMARY OF EVALUATED SHELTER CONCEPTS.

Shelter Type	Small Shelters	Large Shelters
Pole-/Frame-Supported Fabric Shelters	1. Pole-supported fabric shelter 2. Frame-supported fabric shelter 3. Stressed membrane shelter	1. Frame-supported fabric hangar 2. Truss-supported fabric hangar
Air-Inflated/Air-Supported Fabric Shelters	4. Air beam fabric shelter 5. Dual wall inflatable shelter 6. Air-supported fabric shelter	3. Air beam fabric hangar 4. Dual wall inflatable hangar 5. Air-supported fabric hangar
Rigid Panel Shelters	7. Accordion/box shelter 8. Airmobile MERWS 9. Hybrid panel/fabric MERWS 10. Geodesic panel dome	6. Arch/panel hangar
Built-Up, Load-Bearing Wall Shelters	11. Block wall shelter 12. Bin-wall shelter 13. Reinforced earth shelter	7. Bin-wall hangar
Portable Shell Shelters	14. Foam dome 15. K-Span personnel shelter 16. Hypar shell	8. K-Span hangar

chosen to be representative of the broader range of materials and methods considered in the hardening trade studies. The four upgrades considered were: (1) 36 *inches* of soil (free-standing soil bin or shelter-supported berm), (2) 4 *psf* aluminum panels (free-standing revetment or shelter-supported), (3) 4 *psf* S2-glass composite panels (free-standing revetment or shelter-supported), and (4) 4 *psf* Spectra® blankets (shelter-supported only).[1] Upgraded aluminum, S2-glass, and Spectra® configurations were not generated for the shelter concepts that already have soil incorporated into their basic configurations (*i.e.*, small shelter numbers 11-13 and large shelter number 7). The mobility and cost attributes associated with the four hardening upgrades were summarized in Table 37.

We selected the cluster munition at a standoff of 100 *feet* to assess the ASEM survivability attribute for each basic and upgraded shelter concept. For an unprotected shelter (*e.g.*, a conventional fabric shelter), this threat produces approximately 1 perforation per 10 *feet*^{2} of exposed wall area. This perforation density represents our estimate of the threshold at which protection begins to be beneficial and is assigned a utility of zero. The 36-*inch* soil upgrade defeats virtually all of the fragments from the cluster munition at a standoff of 100 *feet* and, as a result, provides a fragment perforation utility of 1.0. The utilities of the remaining three

[1]Although Spectra® blankets were selected for the ASEM hardening upgrade concepts, our current understanding indicates that the attributes of Kevlar® blankets would be would be nearly identical for the types of threats considered in this study. Similarly the performance of KM2 and Spectra® panels are comparable to that for S2/HJ1 panels. Testing will be required in the next phase of the FOPS research program to differentiate these materials on the basis of their hardening, cost, and mobility attributes.

upgrades fall between these two extremes. The 4 *psf* S2-glass panels and Spectra® blankets provide essentially equal levels of protection.

c. Concept Evaluation and Recommendations

In Section IV, we develop and implement a multi-attribute decision analysis tool for comparing and selecting portable shelter design concepts. The Airmobile Shelter Evaluation Methodology (ASEM) requires four major inputs: (1) a hierarchy of design objectives, (2) marginal utility curves for each lowest-level design attribute, (3) a preference set that characterizes the relative priorities placed on the competing design objectives, and (4) the specific design attribute values for each candidate design concept.

There are significant uncertainties and subjective judgments associated with each of the four major ASEM inputs. At this point in the shelter development process, however, AF prioritization of the competing shelter objectives stands out as the dominant source of shelter selection uncertainty. Although we were able to obtain limited AF input on preferences for the four first-level shelter objectives (*i.e.*, mobility, cost, performance, and survivability), deeper interaction and additional iterations will be required to fully develop a consensus on the design priorities for FOPS. Assuming that none of the four first-level objectives is abandoned, we believe that the most effective design solutions will be upgradeable, adaptable shelter concepts. Thus, a major challenge will be to minimize the number of different shelter components so that inventory demands are minimized.

(1) Small Shelter Recommendations.

Under two of the four preference sets (*RWG* and *No-Survivability*), the recommended concept is the basic (*i.e.*, non-upgraded) air beam-supported fabric shelter[1]. For the *RWG* scaling, the air beam is followed by the basic pole-supported tent and the soil bin upgraded airmobile MERWS concept. The third tier of concepts includes the basic dual wall and air-supported fabric shelter concepts as well as the S2-glass panel and Spectra® blanket upgraded airmobile MERWS concepts. Under the *No-Survivability* preference set, basic fabric shelters, led by the air beam and pole-supported shelters, make up the top five concepts. Note that the obstructed interior space of the pole-supported tent and its need for regular inspection/maintenance to ensure stability (two design attributes that are not explicitly considered in the current ASEM model) may render it unacceptable in spite of its good mobility and cost characteristics. The fabric shelters are followed by the basic airmobile MERWS and hybrid MERWS concepts. As expected, none of the upgraded shelter concepts rate well under the No-Survivability scaling since this bounding preference set assigns no priority to shelter hardness.

Under the remaining two preference sets (Equal and No-Cost), the airmobile MERWS concept with the free standing 36-*inch* soil bin upgrade is the highest rated

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[1]Under the *No Survivability* preference set, survivability is given zero priority, and mobility, cost, and performance are given equal priority.

concept[1]. Under the Equal scaling set, the MERWS is followed by six other soil hardened concepts: the block wall, hybrid MERWS, bin wall, hypar shell, geodesic dome, and frame-supported fabric shelters, respectively. The runner-ups under the No-Cost scaling are quite similar with the exception that the reinforced earth C3 shelter concept rises to second place. If soil protected shelter concepts are excluded, the MERWS with shelter-supported S2-glass panels or Spectra® blanket upgrades and the basic air beam shelter become the recommended concepts under Equal scaling.

Cost and mobility are the primary drivers in choosing between S2-glass panels and Spectra® blankets. Preference for low cost favors the S2-glass panels while preference for mobility favors the Spectra® blankets. Under the RWG scaling (which is mid-way between the Equal and No-Cost preference sets in terms of cost priority) the blankets and S2-glass panels are equally preferred upgrades for the MERWS concept.

In summary, two concepts appear most frequently at the top of the small shelter overall utility rankings: the basic air beam fabric shelter and the upgraded airmobile MERWS configurations. Of the non-fabric shelters, the airmobile MERWS concept is the leading overall concept for all four preference sets. Therefore, we recommend that the hardened airmobile MERWS concepts should be the focus of the next phase of the research program. If satisfactory hardening levels cannot be achieved or if the mobility and cost penalties prove to be beyond AF constraints, we recommend that a new generation of unhardened air beam (*i.e.*, pressurized rib) supported fabric shelters be pursued as a high payoff approach to shelter mobility and cost.[2] A low-risk alternative fabric concept that rates better with respect to performance and structural reliability is the frame-supported fabric concept. The hardening technology developed under further research for the MERWS system will also be directly applicable to an upgraded frame-supported hybrid fabric/panel concept. Thus, the frame-supported fabric concept should be kept under consideration as a low-risk back-up alternative.

(2) **Large Shelter Recommendations.**

Under three of the four preference sets used in the shelter evaluation studies, the basic and upgraded arch-supported panel and bin wall hangars are consistently ranked as the leading concepts. The No-Survivability preference set is the only case under which the arch/panel and bin wall concepts do not rate the best. When survivability is given little or no priority, the basic air beam and frame-supported fabric shelter concepts excel. However, even under the No-Survivability preference set, the basic arch/panel and bin wall hangar concepts are competitive with the fabric hangar concepts. For survivability scaling factors equal to or in excess of the preference levels inferred from the RWG survey, the basic and upgraded arch/panel and bin wall hangar concepts outperform the fabric hangar concepts.

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[1]Under the No Cost preference set, cost is given zero priority, and mobility, performance, and survivability are given equal priority.

[2]At present, there is no packing ratio threshold or objective specified in the ORD. After a transportability threshold is specified in a future revision of the ORD, it is possible that the MERWS will not meet the packing ratio requirement.

For the arch/panel concept, the soil bin, S2-glass panel, Spectra® blanket upgrade configuration utilities approximately meet or exceed the overall utilities of the basic, unhardened concept. For the bin wall concept, the only upgrade considered is an increased wall thickness with 36 *inches* of soil infill. The overall utility of the upgraded bin wall concept is also similar to or better than that of the basic bin wall concept (which has only 12 *inches* of soil). In both cases, the relative utilities of the hardening upgrades improve as the importance placed on survivability is increased.

We recommend that the arch/panel and bin wall hangar concepts be studied in parallel. The arch/panel concept is basically an upgradeable version of the current Harvest Bare ACH shelter. Therefore, a complete preliminary design of the arch panel concept should be relatively straightforward. In addition, much of the experimental program required to verify the protection provided by the recommended airmobile MERWS small shelter concept will be directly applicable to the evaluation of upgraded arch/panel hangars. Since the preferred portable hangar concept will ultimately depend on whether our estimates for the bin wall design attributes can be met or exceeded, we also recommend that a preliminary structural design and analysis of the basic and upgraded bin wall concepts be developed early in the next phase of the FOPS research program.

The feasibility of the bin wall concept will be determined by three key issues: (1) the required hardness level, (2) the acceptability of soil-based hardening methods and (3) the developmental uncertainties associated with the bin wall hangar concept. Therefore, further probing of AF preferences regarding hardening requirements and hardening methods will be necessary, and detailed design studies on the structural feasibility of the bin wall concept will be required in the next phase of the FOPS development program. Some specific issues include: lateral stability under wind and blast loads, hangar deployment without the use of soil to fill-in the bin walls, wall/roof connections, packaging concepts, and rapid assembly concepts.

After a more detailed cycle of design and analysis on the arch/panel and bin wall hangar concepts is complete, a reevaluation of the two concepts should be performed. Additional AF prioritization inputs should also be gathered before the final hangar concept is selected.

As with the small shelter recommendations, there is a real possibility that when posed with the mobility and cost penalties of the recommended rigid wall hangar concepts, the ultimate preferences of AF decision makers may be to abandon the goal of hardened portable shelters. In this case, the No-Survivability preference set would be the most applicable model, and we would recommend that the basic air beam hangar concept be pursued as a high payoff approach to shelter mobility and cost with a low risk back-up alternative being the frame-supported fabric hangar concept. These recommendations are consistent with our alternative recommendations for the small shelter concepts.

B. RECOMMENDED ROADMAP FOR SHELTER DEVELOPMENT

In Figure 125, we present the recommended roadmap for follow-on shelter research and development. In constructing this roadmap, we continue to limit the scope of the development effort to two members of the FOPS: (1) a small shelter for use as billeting, offices, etc., and (2) a large span shelter for aircraft maintenance. We assume that one prototype for each of the two shelter sizes will be fabricated and tested (a scaled prototype for the large shelter may be required to reduce costs). The prototype testing will include both hardness and environmental testing. We also assume that at least one additional Requirements Working Group (RWG) meeting will be held to clarify the shelter priorities resulting in some form of consensus on shelter requirements within the first nine months of FY 93. Third, we assume that the six weapon threats modeled in this study will form the core weapon threats for the remainder of the program. If additional weapons are to be considered, these weapons can be characterized and assessed in FY93; however, they need to be specified as soon as possible. Finally, hardness assessments for combined airblast and fragment impulses will be required after survivability against fragment perforation is demonstrated. An analysis model for combined airblast and fragment loads will be required to optimize the preliminary shelter designs and to design the prototype hardness tests in FY94.

Concurrent with the preliminary design stage, we recommend fabrication and testing (combination of gun range and weapon effects tests) of components for the leading hardening concepts (panels, fabrics, *etc.*). The purpose of these tests are to: (1) fill in gaps in currently available test data, (2) improve and calibrate the SAFE methodology presented in Section III, (3) provide residual velocity data for a new SAFE personnel survivability module, (4) screen hardened panel designs, and (5) confirm the preferred hardening configurations and materials. The design and planning for these tests should begin in early FY 93.

After completing the preliminary design stage, the component hardening tests, and revisions to the SAFE and ASEM codes, we recommend performing a final assessment and ranking of the preliminary designs. With the preliminary designs in hand, we can quantify the shelter attributes much more accurately than possible in the present study. Therefore, the uncertainties in the shelter ratings will be significantly reduced. There will also be an opportunity at this point, to update Air Force inputs to the preference sets. Based on these results, one small and one large shelter will be recommended for prototype design, fabrication, and testing.

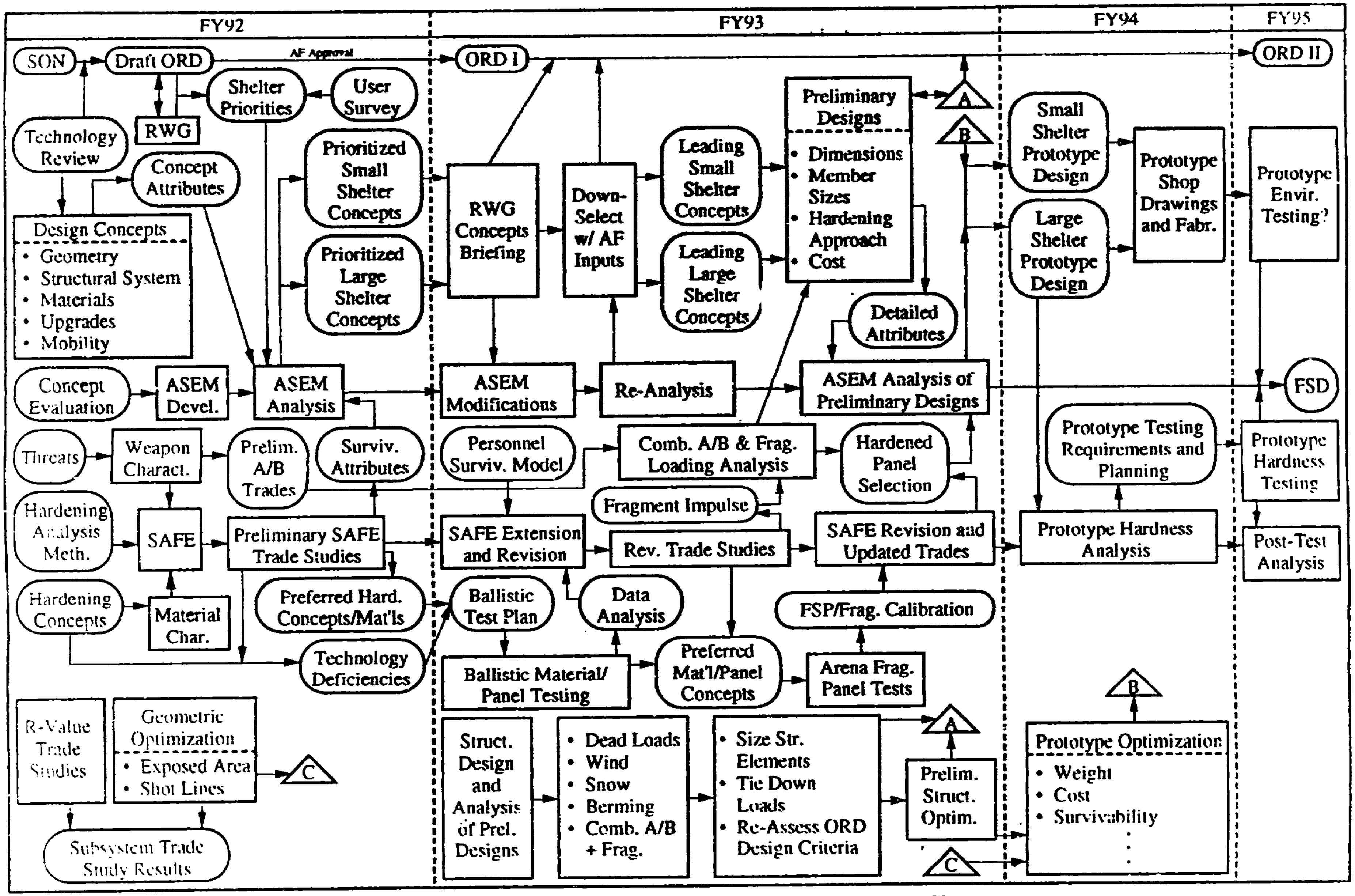

Figure 125. Proposed Airmobile Shelter Development Flow Chart.

The recommended schedule for prototype shelter development is longer than that specified in the airmobile shelter program area document (PAD). We believe that the time allotted for prototype design, construction, and testing of FOPS in the PAD is overly optimistic. Therefore, we have set early FY 95 as the target for prototype hardness tests. It is not possible to start these activities earlier since the schedule for ballistic and weapon effects testing on components cannot be realistically compressed. We believe that the time spent in developing and evaluating a good set of preliminary designs; in developing, analyzing, and testing hardening approaches; and in developing AF consensus on shelter priorities through RWG interaction will pay significant returns.

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APPENDIX A

AIRMOBILE SHELTER GLOSSARY AND ACRONYMS

A. AIRMOBILE SHELTER GLOSSARY[1]

- ***Bare Base.*** A base having a runway, taxiways, parking areas adequate for the deployed force, and possessing an adequate source of water that can be made potable [AFP 93-12].

- ***Collocated Operating Base (COB).*** A base hosted by an ally that can be used to beddown Air Force augmenting forces. COBs require civil engineering support to accommodate reception, beddown, launch, and recovery of USAF aircraft. A COB may be a main, standby, or limited base of the allies [AFP 93-12].

- ***Concept Studies.*** Studies conducted to evaluate and define the feasibility of alternative concepts. They provide the basis for assessing the relative merits of alternative concepts. They provide the basis for assessing the relative merits of alternative concepts at the MS I decision point [AFR 57-1].

- ***Container.*** An article of transport equipment —

  (1) Designed to be transported by various means.
  (2) Having interior volume of 400 *feet*^{3} or more.
  (3) Designed for the best transportation of goods by one or more means without intermediate handling of contents.
  (4) Equipped for ready handling and transfer from one means of transportation to another.
  (5) That may be fully enclosed with one or more doors, open top, refrigerated tank, open rack, gondola, and other designs.
  (6) So configured as a module or cluster that it can be coupled to form a unit with 400 or more cubic feet internal capacity. This is a container regardless of whether it will be moved singly or in multiplex [AR 70-59].

- ***Critical System Characteristics.*** Those performance parameters or characteristics so important to the program that failure to obtain the associated thresholds would be cause for program reassessment or termination [AFR 57-1].

- ***DOD Tactical Shelter Program.*** The shelter RDTE requirements of the Services formulated by JOCOTAS and approved by the Office of the Secretary of Defense (OSD). Primarily, the program consists of RDTE management documents such as DD Form 1634 (Research and Development Planning Summary) and DD Form 1498 (Research and Technology Work Unit Summary). This program documents —

  (1) Provides OSD a description of the work to be performed within fiscal guidance.
  (2) Identifies the areas where additional funds are required.
  (3) Provides the guidance for execution of the program. The objective of the DOD Tactical Shelter Program is to:
      (1) Reduce duplication of effort.
      (2) Achieve maximum standardization within DOD.

[1]Primarily Obtained from: (1) AFP 93-12, Attachment 2; (2) AFR 57-1, Attachment 1 (Effective 7 October 1988); and (3) Revised Draft AFR 57-1, Attachment 8 (22 October 1990).

(3) Plan and control the tactical shelter program according to changing military needs.

Examples of elements included in the DOD Tactical Shelter Program are as follows:

(1) Space requirement for performing a function.
(2) Environmental protection requirement for function continuity.
(3) Operational response (mobility and the reaction time).
(4) Requirements of the separate functions to be sheltered such as:
  (a) Light-proofness.
  (b) Fire-resistance.
  (c) Camouflage deception.
  (d) Electrical grounding.
  (e) Electromagnetic interference (EMI)
  (f) Radio frequency interference (RFI)
  (g) Chemical/biological protection
  (h) Hardening.
  (i) Noise suppression.
(5) Tactical shelter analysis, structures, physics, heat transfer, processing, preservation, user acceptance, human factors, specifications, service components, materials, and facilities for all environments and all operating conditions.
(6) Verification testing as required.

It is DOD policy that ANSI/ISO criteria will be applied in tactical shelter development, if practical.

The Department of the Army is the lead component in the Tactical Shelter Program [AR 70-59].

- ***Force Beddown.*** Providing minimum expedient facilities necessary for deployed units to become operationally ready (OR) and to survive enemy attack [AFP 93-12].

- ***Harvest Bare.*** Nickname given to a bare base system. Harvest Bare is a concept in mobility which offers deployment of all supporting buildings to a bare or fixed base. These buildings are lightweight, modular design, and may serve as containers for items being used to set up the building. Harvest Bare consists of shelters, utilities, and base maintenance equipment and support subsystems. Harvest Bare assets are designed to support 4,500 personnel in various increments and are designated as War Reserve Materiel (WRM) and maintained in ready-to-deploy status [AFP 93-12].

- ***Harvest Eagle.*** Harvest Eagle is a nickname given to a selected package of essential items of equipment and supplies required to support forces and personnel under bare base conditions. It is an air tranportable housekeeping package designed to support activities deployed to remote areas where it is not feasible to preposition assets. Harvest Eagle sets are designed to support 1,100 personnel and are designated War Reserve Materiel (WRM) and maintained in ready-to-deploy status [AFP 93-12].

- ***Human Factors Engineering (HFE).*** Human performance as an integral part of total system or equipment performance [AFR 57-1].

- ***Implementing Command.*** The command or agency designated by the Air Force Acquisition Executive to manage an acquisition program. (DODI 5000.2) [AFR 57-1].

- *Integrated Logistics Support (ILS).* A disciplined, unified, and iterative approach to the management of technical activities necessary to: (a) integrate support considerations into system and equipment design; (b) develop support requirements that are related consistently to readiness objectives, to design, and to each other; and (c) acquire the required support; and (d) provide the required support during the operational phase at a minimum cost [AFR 800-8].

- *Joint Committee on Tactical Shelters (JOCOTAS).* JOCOTAS is established to obtain the coordination of all Military Services in developing the DOD Tactical Shelter Program. This committee integrates all tactical shelter requirements from the Military Services and DOD components [AR 70-59].

- *Limited Base (LB).* A base that is austerely manned and normally has no permanently assigned operational tactical forces, but may possess a small force for special operations (weather surveillance, alert aircraft, special purpose aircraft, etc.). With personnel augmentation, this base is capable of receiving deployed forces. It may have facilities for communications, air traffic control, navigational aids, maintenance, base supply, munitions, weather, medical services, billeting, messing, transportation, and operational support. It may or may not be supported in peacetime as a satellite of a main base. WRM, including POL, may be maintained in a state of readiness for use by the deploying force to initiate and sustain operations; however, additional support personnel and equipment must be maintained [AFP 93-12].

- *Main Operating Base (MOB).* A base on which all essential buildings and facilities are erected. Total organizational and intermediate maintenance capability exists for assigned weapon systems. The intermediate maintenance capability may be expanded to support specific weapon systems deployed to the MOB [AFP 93-12].

- *Milestones (0-IV).* Major management decision points in the overall acquisition decision process of a DOD system requiring OSD and/or DOD component program review. Milestones include both DAB and DOD component-equivalent program reviews.

  - 0 — Concept Studies Approval
  - I — Concept Demonstration Approval
  - II — Development Approval
  - III — Production Approval
  - IV — Major Modification Approval

  [AFR 57-1].

- *Mission Need Statement (MNS).* A document prepared to identify a requirement for a material solution to satisfy a mission deficiency [AFR 57-1].

- *Objective.* A value beyond the threshold that could potentially have a measurable, beneficial impact on capability or operations and support above that provided by the threshold value (DODI 5000.2) [AFR 57-1].

- *Operating Command.* The command primarily operating a system, subsystem, or item of equipment. Generally applies to those operational commands or organizations designated by HQ USAF to conduct or participate in operations or operational testing (AFM 11-1). Interchangeable with the term using command [AFR 57-1].

- ***Participating Command.*** A command or agency designated by the Air Force Acquisition Executive to advise the program manager and to take an active part in the development of a weapon system. The supporting command is also a participating command [AFR 57-1].

- ***Phases (0-IV).*** The acquisition phases provide a logical means of progressively translating broadly stated mission needs into well-defined system-specific requirements:

  - 0 — Concept Exploration and Definition
  - I — Demonstration and Validation
  - II — Engineering and Manufacturing Development
  - III — Production and Deployment
  - IV — Operations and Support

  (DODD 5000.1) [AFR 57-1].

- ***Preplanned Product Improvement (P3I).*** An evolutionary approach designed to minimize technological risk and shorten the time required to field new weapon systems. The approach envisions deliberate planning for use of less advanced technologies initially in a system while consciously planning to incorporate more advanced technologies after the system is placed in operation [AFR 57-1].

- ***Prime BEEF.*** A HQ USAF, MAJCOM, and base-level program that organizes civil engineering forces for worldwide direct and indirect combat support roles. It assigns civilian employees and military personnel to both peacetime real property maintenance and wartime engineering functions [AFP 93-12].

- ***Prime RIBS.*** Worldwide combat services forces organized and trained for wartime support [AFP 93-12].

- ***Program Management Directive (PMD).*** The official HQ USAF management directive used to provide direction to the implementing and participating commands and satisfy documentation requirements. It will be used during the entire acquisition cycle to state requirements and request studies as well as to initiate, approve, change, transition, modify, or terminate programs. The content of the PMD, including the required HQ USAF review and approval actions, is tailored to the needs of each individual program. (AFM11-1, Volume I) [AFR 57-1].

- ***RED HORSE.*** RED HORSE squadrons are HQ USAF controlled squadrons established to provide the AF a highly mobile, self-sufficient, rapidly deployable civil engineering capability required in a potential theater of operations [AFP 93-12].

- ***Requirements Correlation Matrix (RCM).*** A three-part matrix spreadsheet used to provide a system audit trail. It contains a comparison of the user's system needs and requirements, contractual specifications, and operational evaluation criteria (AFM 11-1) [AFR 57-1].

- ***Shelter Classes.***

  - ***Class 1.*** Non-Expandable shelters are used in the same size and shape in which they are transported.
  - ***Class 2.*** Expandable shelters are expanded from the transport size to a larger size, at expansion ratios of 3:1 or less and perhaps different shape, for use as shelters.
  - ***Class 3.*** Highly expandable shelters have expansion ratios greater than 3:1 from their transport size.

- *Class 4.* Knockdown shelters are reduced in height and nested with identical items for transportation (*e.g.*, Marine Corp knockdown shelter).
- *Class 5.* Large area shelters are disassembled and packed in dedicated or general-purpose containers for shipment.

The shelters are further classified as ISO or non-ISO depending on whether they can be transported as containers in accordance with the standards of the International Organization for Standardization (ISO).

MIL-STD-907B applies to ISO or non-ISO shelters in Classes 1-4. At the time MIL-STD-907B was issued, separate standards for Class 5 were in preparation for future implementation as a change or as a separate standard [MIL-STD-907B].

- ***Standby Base (SB).*** An austere base designated for wartime use having adequate airfield facilities to accept deployed aircraft. An SB is maintained in a caretaker status until it is fully augmented, at which time it is capable of receiving and employing assigned aircraft. To initiate and sustain operations, all supporting personnel, supplies, and equipment must be provided. POL and munitions may be prepositioned in a state of readiness for use by the deploying force [AFP 93-12].

- ***Survivability.*** Capability of a system to accomplish its mission in the face of an unnatural (manmade) hostile, scenario-dependent environment. Survivability may be achieved by avoidance, hardness, proliferation, or reconstitution (or a combination) (AFM 11-1) [AFR 57-1].

- ***System Characteristic.*** Performance parameter stated in terms of threshold and/or objective values, needed for a system to accomplish approved military objectives, missions, or tasks [AFR 57-1].

- ***System Threat Assessment Report (STAR).*** An assessment of foreign capabilities that affect the viability, effectiveness, or design of the system. A STAR is the single authoritative reference for threat information pertaining to an acquisition program. It is maintained current to within 12 *months* through production decision. It is prepared by the implementing command, reviewed by the operating command, and approved by HQ USAF/IN. For DAB-level programs, it is subsequently validated by DIA. (AFR 200-13) [AFR 57-1].

- ***Tactical Shelter.*** A presized, transportable structure designed for a functional requirement and which provides a live-in or work-in capability. This structure can be either rigid or expandable. The following are not considered tactical shelters:

  (1) Fabric-wall shelters.
  (2) Air-supported shelters.
  (3) Refrigerated shelters.
  (4) Modular or prefabricated structures designed to be shipped to the theater of operations and assembled with external engineer unit support.
  (5) Containers.
  (6) Equipment vans.
  (7) Fighting positions [AR 70-59].

- ***Threshold.*** Minimum acceptable value for a performance parameter necessary to provide an operational capability that will satisfy the mission need (DODI 5000.2) [AFR 57-1].

- ***War and Mobilization Plan (WMP).*** The USAF WMP is published in five volumes to fulfill the USAF requirement for a plan in support of the joint strategic capabilities plan (JSCP) and DOD mobilization planning directives. Volume 1 is the Wartime Planning Guide, and Volume 3 is the Unit Type Code (UTC) description. The UTC identifies a specific type or kind of force [AFP 93-12].

- ***War Reserve Materiel (WRM).*** Materiel required in addition to peacetime assets to support the planned wartime activities reflected in the U.S. Air Force War and Mobilization Plan (WMP) [AFP 93-12].

B. SELECTED ACRONYMS AND ABBREVIATIONS[2]

ABO	Air Base Operability
ABS	Air Base Survivability
ACAT	Acquisition Category
ACE	Allied Command Europe
ACH	Aircraft Maintenance Hangar (Harvest Bare)
AF	Air Force
AFB	Air Force Base
AFCC	Air Force Communications Command
AFCESA	Air Force Civil Engineering Support Agency
AFLC	Air Force Logistics Command
AFM	Air Force Manual
AFOTEC	Air Force Operational Test and Evaluation Center (Kirtland AFB)
AFP	Air Force Pamphlet
AFR	Air Force Regulation
AFSC	Air Force Specialty Code, or Air Force Systems Command
AGE	Airfield Ground Equipment
ALCE	Air Lift Control Element
ANG	Air National Guard
AO	Area of Operations
ASD	Aeronautical Systems Division (Wright-Patterson AFB)
ATC	Air Transportable Clinic
ATH	Air Transportable Hospital
BCE	Base Civil Engineer
BCM	Baseline Correlation Matrix (also see RCM)
C3	Command, Control, and Communication
C3CM	Command, Control, and Communications Countermeasures
CBW	Chemical-Biological Warfare
CCA	Contamination Control Area
CCD	Camouflage, Concealment, and Deception
CESP	Civil Engineering Support Plan
COB	Collocated Operating Base
COEA	Cost and Operational Effectiveness Analysis
CONEX	Consolidated Express (Containers)
CP	Chemical Protection
CPG	Conceptual Planning Guide (AFP 93-12, Vol. III)
CW	Chemical Warfare
DCS	Deputy Chief of Staff
DMC	Depot Maintenance Concept

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[2]Primarily Obtained from: (1) AFP 93-12, Attachment 2; (2) AFR 57-1, Attachment 1 (Effective 7 October 1988); and (3) Revised Draft AFR 57-1, Attachment 8 (22 October 1990).

DOC	Designed Operational Capability
DOD	Department of Defense
DPG	Defense Planning Guide
DT&E	Development Test & Evaluation
EMI	Electromagnetic Interference
EMP	Electromagnetic Pulse
ERD	Evolutionary Requirements Definition
ESC	Expandable Shelter Container (Harvest Bare)
ESD	Electronic Systems Division (Hanscom AFB)
EXP	Expandable Personnel Shelter (Harvest Bare)
FOB	Foward Operating Base
FOC	Full Operational Capability
FOPS	Family of Portable Shelters
FOT&E	Follow-on Operational Test & Evaluation
FRP	Full-Rate Production
FSD	Full Scale Development
GP	General Purpose (Harvest Bare GP rigid wall shelter)
GPL	General Purpose Large (Harvest Eagle tent)
GPM	General Purpose Medium (Harvest Eagle tent)
HB	Harvest Bare
HE	Harvest Eagle
HEAT	High Explosive Antitank (missile)
HMMWV	High Mobility Multipurpose Wheeled Vehicle
ILS	Integrated Logistics Support
ILSP	Integrated Logistics Support Plan
IOC	Initial Operational Capability
IOT&E	Initial Operational Test and Evaluation
IR	Infrared
ISO	International Standardization Organization
JCS	Joint Chiefs of Staff
JOCOTAS	Joint Committee on Tactical Shelters
JSP	Joint Support Plan
LAW	Light Antitank Weapons
LB	Limited Base
LCC	Life Cycle Costs
LCN	Load Classification Number
LDS	Lightweight Decontamination System
LN	Logistics Needs
LOX	Liquid Oxygen
LRIP	Low Rate Initial Production
LTA	Low Threat Area
MAC	Military Airlift Command
MAJCOM	Major Command
MCPE	Modular Collective Protection Equipment (MCPE)
MHE	Materiel Handling Equipment (*e.g.* 463L)
MNS	Mission Need Statement (also see SON)
MOB	Main Operating Base
MOBSS	Mobility Support Squadron
MPT	Manpower, Personnel, and Training
NAVAIDS	Navigational Aids
NBC	Nuclear, Biological, Chemical
NEW	Net Explosive Weight
NSN	National Stock Number
O&M	Operation and Maintenance

OPR	Office of Primary Responsibility
ORD	Operational Requirements Document (also see SORD)
OT&E	Operational Test and Evaluation
OPLAN	Operations Plan
OUSD(A)	Office of the Under Secretary of Defense (Acquisition)
P3I	Preplanned Product Improvement
PACAF	Pacific Air Forces
PAPS	Periodic Armament Planning System (NATO)
PD	Program Director
PDP	Program Decision Package
PM	Program Manager (*e.g.*, Norm Bedard for PMD 1016: Tact. Shelters)
PMD	Program Management Directive
PMP	Program Management Plan
POC	Point of Contact
POL	Petroleum, Oil, and Lubricants
Prime BEEF	Prime Base Engineer Emergency Force
Prime RIBS	Prime Readiness in Base Services
RCM	Requirements Correlation Matrix (also see BCM)
RDF	Rapid Deployment Force
R&D	Research and Development
RD&A	Research, Development, and Acquisition
RED HORSE	Rapid Engineer Deployable Heavy Operational Repair Squadron, Engineer
R&M	Reliability and Maintainability
RRR	Rapid Runway Repair
SAC	Strategic Air Command
SCNS	Standard Camouflage Net System
SCPS	Survivable Collective Protection System (US version of AMF-80)
SOA	Separate Operating Agency (*e.g.*, AFCESA is an SOA)
SON	Statement of Need (also see MNS)
SORD	System Operational Requirements Document (also see ORD)
SPO	System Program Office
SRR	Survival, Recovery, and Reconstitution
STAMP	Standard Air Munitions Package
STAR	System Threat Assessment Report
SWA	Southwest Asia
TA	Table of Allowances
TAC	Tactical Air Command (Langley AFB)
TAFB	Tyndall AFB
TBD	To Be Determined
TCPS	Transportable Collective Protection Shelters
TDY	Temporary Duty
TEMP	Test and Evaluation Master Plan
TEMPER	Tent, Extendable Modular Personnel
TM	Technical Manual
TOA	Total Obligational Authority
TO	Technical Order
TPD	Threat Planning Document
USAF	United States Air Force
USAFE	United States Air Forces, Europe
WDR	War Damage Repair
WMP	War and Mobilization Plan
WPAFB	Wright-Patterson AFB
WRM	War Reserve Materiel

APPENDIX B

OPERATIONAL REQUIREMENTS DOCUMENT

OPR: Maj Wilderman
HQ ACC/DRWC
DSN 574-7596

DATE:

OPERATIONAL REQUIREMENTS DOCUMENT

FOR

NEW FAMILY OF PORTABLE SHELTERS

1. General Description of Operational Capability.

a. A new family of air-transportable shelters is an operational capability required to support OUSD(A) mission areas #220, Air Warfare; and #225, Air Warfare Support.

(1) Current portable shelters are bulky, hard to erect and maintain, provide only limited environmental protection, and are the product of decades-old technology. New technology developments offer the potential for a reduction in weight and volume with comparable savings in labor and erection machinery. The new family of portable shelters (FOPS) will provide significantly upgraded performance and technology over current USAF portable shelters. FOPS must be capable of being used with existing portable shelter equipment.

(2) TAF SON 314-88, New Family of Portable Shelters, validated 2 Nov 90, documents the need for a new family of air-transportable shelters to significantly upgrade the performance of USAF portable shelters. Portable shelters are used in bare base deployments and to support other rapidly deployed mobility forces. The shelters will be general purpose in nature, providing facilities, administrative offices (to include command and control), maintenance shops, aircraft hangars, storage, and other support facilities. The primary goals of this effort are to improve the logistical and operational characteristics (e.g., transportability, volumetric packing ratio, weight, rapid erection, environmental control, durability, geometry, and cost/performance ratio) over existing USAF portable shelters and provide some inherent and/or upgradeable levels of protection against conventional and unconventional weapon threats.

(3) To achieve the performance objectives, the FOPS will employ innovative modern technology in the areas of composite materials, structural systems and geometries, fabrication and erection methods, hardening methods, and energy transfer. New technology developments for shelter construction offer the potential for reducing weight, shipping volume, labor, and/or erection machinery. These savings will minimize shelter demands on the transport system and engineering assets, enhancing the ability to rapidly establish and support air power where and when needed. New technological developments in the field of

lightweight and ballistic resistant composite materials offer potential for providing reasonable protection against weapon fragmentation without undue sacrifice of transportability. New technologies offer the potential to enhance nuclear, biological, and chemical (NBC) protection as an integral structural component of the shelter system. New technologies and innovations in the construction industry offer possibilities to provide portable, lightweight building systems which would exploit the use of indigenous materials to produce operational and support facilities.

(4) The Air Force will operate from various main and collocated operating bases in European, Pacific, Southwest Asian, and other theaters to support combat operations. AFP 93-12, Vol III, Bare Base Conceptual Planning Guide, and Vol IV, Establishing and Maintaining a Theater Expeditionary or Base, document operational and support concepts for bare base shelters. Shelters are anticipated to be prepositioned at staging areas in theaters of operation, stored in the CONUS awaiting deployment, or stored for use in exercises and training. Consequently, operational contingency planning must include both intertheater and intratheater transport.

b. Requirements Correlation Matrix. See Atch 1.

2. **Threat.**

a. The Air Force Intelligence Command Foreign Technology Center-developed and Defense Intelligence Agency-validated, "Threat Compendium, Worldwide Threat to Air Bases: 1991-2001," 31 Dec 91, is the baseline threat reference for air base operability acquisition-related issues. Because of the wide variety of possible operating locations and potential adversaries, a broad range of air and ground threats can be expected. These include a liberal mix of iron bombs, precision guided munitions, anti-personnel/vehicle mines, chemical and biological weapons, saboteurs, special operations forces, and general purpose offensive ground forces. FOPS will optimize design aspects to provide reasonable protection against these threats.

b. USAF/IN Approved or DIA Validated STAR. Not applicable.

3. **Shortcomings of Existing System.**

a. Air Force portable shelters fall in two distinct programs--the Bare Base Program (BBP) and the Tactical Shelter Program (TSP). The BBP includes Harvest Bare hardwall shelters, Harvest Falcon hardwall and softwall shelters, and Harvest Eagle softwall shelters. With the exception of the TEMPER, Harvest Program shelters are bulky, hard to erect and maintain, provide only limited environmental protection, and are the product of decades-old technology. The TSP includes a DOD standard family of tactical shelters designed to meet the requirements of all services. These shelters are both expandable and nonexpandable unitized shelters designed to be transported by land, sea, or air. The TSP specifically excludes fabric wall shelters (tents), air-supported structures, refrigerated buildings, cargo containers, and prefabricated buildings, or structures.

b. TEMPER. The TEMPER is a modular, fabric shelter supported by an aluminum frame structure. The fabric is made of synthetic material and, although it provides no splinter protection, can afford some chemical warfare protection when the collective protection liner is installed. Fabric in the existing inventory of tents does not provide visual or image intensification blackout, although upgraded fabrics with blackout capability now exist. Ultraviolet deterioration of the synthetic material used in some TEMPER components shortens the shelter's life expectancy. Existing floor and door mechanisms (to include zippers) are not sufficiently durable for extended deployments. For this reason, users frequently replace the TEMPER's soft floors and entrances with rigid materials to make the shelter more operable.

d. Bare Base Hardwall Shelters. Bare base hardwall shelters include: The Expandable Personnel Shelter, the Expandable Shelter/Container, the General Purpose Shelter, and a 76-foot by 125.6-foot aircraft maintenance hangar. These panel shelters are more durable than softwall pole and frame supported tents. Air-conditioning can be added, and blackout curtains are available on most shelters. Current shelters are highly vulnerable to collateral damage from nearby bomb bursts, will not provide a chemical-free environment, and are not easily decontaminated. They are difficult to maintain because of the high cost and difficulty in obtaining replacement parts.

e. Tactical Shelters. Tactical shelters typically have low packing ratios and are too small for many bare base functions. Additionally, the International Organization for Standardization (ISO) shipping/storage container standards used in tactical shelters are not completely C-130 aircraft/463L pallet system-compatible and require special handling. The ISO container standards also impose a weight penalty.

4. **Capabilities Required.**

a. System Performance. FOPS will be employed largely through airlift as part of established and next generation bare base deployment packages and through prepositioning.

(1) Performance Parameters.

(a) FOPS will provide suitable structures for the following functions:

1. Personnel billets.

2. Command and control.

3. Administrative offices and shops.

4. Latrine and shower facilities.

5. Vehicle maintenance and repair shops.

6. Supply warehouses.

7. Medical facilities.

8. Aircraft maintenance hangars.

9. Kitchen/feeding facilities.

10. Munitions storage facilities.

(b) FOPS design and components will be standardized as much as possible.

(c) FOPS must be no more difficult to unpack, erect, strike, and repack than the current shelters under any condition.

(d) FOPS erection times will be minimized to the maximum extent possible to significantly improve on erection times of existing systems. Aircraft shelters must be erectable in no more than 120 man-hours each--80 man-hours desired. Personnel shelters will be erectable by no more than four personnel in no more than two man-hours per 150 square feet of floor space--200 feet desired. A 50 bed air transportable hospital must be erectable in no more than 24 hours. Other shelters will have comparable erection times.

(e) FOPS will be erectable by personnel wearing full chemical warfare ensemble and cold weather clothing.

(f) FOPS will provide reasonable hardness protection (at least splinter protection) for all shelters. Hardness protection will be a characteristic of the shelter construction, or a result of optional upgrade kits or field-expedient methods using available local materials.

(g) All FOPS components must be ruggedized for field use, portable, and reliable.

(h) All FOPS components must be simple to operate, store, and maintain.

(i) Chemical and biological protection will be provided as either a characteristic of the shelter construction or as a result of optional upgrade kits.

(j) The FOPS must be capable of being easily decontaminated using nondestructive methods and equipment. Decontamination procedures will be a consideration of design concept development.

(k) FOPS will be compatible with current camouflage, concealment, and deception technology and provide visual and image intensification blackout, preferably without the aid of a liner, and without the need for an electrical power outage.

(l) Electromagnetic interference/radio frequency interference protection will be considered for smaller shelters that may house electronic equipment.

(m) FOPS must permit the ventilation of trapped fumes, smoke, steam, or heat from maintenance, food service, personnel support, medical, and billeting areas.

(n) FOPS must have the capability to interface with available utilities (sewer, water, electricity), and include support connections for lights and built-in (or modification kits for, electrical outlets). Lights appropriate to the shelter's intended function will be included.

(o) FOPS will have environmental control (heating and air-conditioning) or be compatible with standard systems. Solar screens and insulation will be included to minimize HVAC need/demand.

(p) FOPS will be capable of worldwide operations and deployment without degradation under all climatic conditions. Climate adaptation kits will be developed to provide/achieve this capability.

(q) All shelters must be able to withstand sustained winds of 80 mph with gusts to 100 mph.

(r) FOPS roofs must support or shed a snow load of 10 pounds per square foot and withstand a solar load sufficient to raise the outer skin temperature to 205 degrees F. with no evidence of permanent deformation. All shelters must also be able to withstand the ultraviolet effects of sunshine without degradation of components for the service life of the shelter. Environmental requirements for weather seals, air tightness, humidity, marine atmosphere, low temperature, temperature shock, heat transfer, blowing sand, ultraviolet effects, solar loads, and water tightness will be IAW MIL-STD-907B, Sections 5.2 and 5.3.

(s) FOPS must include suitable and expedient flooring. Rigid floors and hinged doorways are desirable for improving shelter durability and operability. Shelters must include flooring systems functional under various environments and terrain (e.g., permafrost, sand, and rock). These systems may either be integral to the shelter or provided as an add-on kit for site specific use.

(t) FOPS will include suitable storage/transportation containers to provide environmental/movement protection.

(u) FOPS will include suitable repair kits for field level repair.

(v) FOPS will, to the maximum extent possible, utilize simple, quick-disconnect type fastening systems as opposed to screws, bolts, and nuts.

(w) Hinges, pins, fasteners, and components requiring maintenance and periodic replacement will be off-the-shelf and have spares provided with the shelter.

(x) Mission scenarios for the FOPS will be divided into three phases: predeployment, deployment, and postdeployment.

1. Predeployment. FOPS will be stored in shipping containers in warehouses or open storage requiring no more than standard upkeep/maintenance practices. Appropriate add-on/upgrade/repair kits for the deployment area will accompany FOPS.

2. Deployment. On deployment notification, FOPS will be moved from storage, checked for serviceability, and marshalled for shipment/erection.

3. Postdeployment. When deployment operations end, FOPS will be decontaminated (if necessary) to allow safe striking, inspected for damage, repaired (if field level repair is available or required), cleaned, repacked for reuse and returned to storage.

(y) FOPS must be as lightweight and compact as possible without compromising other required characteristics.

(z) FOPS must be resistant to corrosion and other environmental deterioration and coated consistent with need and state-of-the-art in both preservation and camouflage. FOPS materials, parts, and corrosion prevention techniques will be IAW MIL-STD-808A.

(aa) Anchoring kits will be provided for adverse soils/pavements.

(2) SEEK EAGLE Requirements. Not applicable.

b. Logistics and Readiness.

(1) Operational Availability.

(a) Portable shelters must be erectable, operable, maintainable, and repairable in all types of conventional warfare environments (including chemical and biological). These functions must be accomplished by military personnel with limited training on the shelters. Simple, effective repair procedures will be designed and deliverable.

(b) FOPS will be capable of repeated use during routine operations and training exercises with a minimum of servicing and maintenance. Small shelters must be able to withstand at least 12 cycles--26 desired--of assembly to the operational configuration and disassembly to the packed configuration for the 20 year life of the shelter. Large shelters must withstand 12 assembly/disassembly cycles--20 desired for the life of the shelter.

(c) FOPS continual use life must allow prolonged use of up to a minimum of one year--two years desired.

(d) Shelters will be designed for open storage warehousing in 463L pallet system-compatible containers for at least five continuous years--10 years desired--with no degradation of design performance and with minimal inspection and maintenance.

(e) FOPS and components (if any) to be stored must have a shelf life of at least 20 years and not require routine maintenance during storage.

(f) FOPS must operate normally after extended storage with no more than minor field level maintenance.

(g) FOPS will be resistant to the deteriorating effects of weather, climate, and long term storage; and sufficiently versatile in design so as to fulfill diverse needs and prevent proliferation of variety and types which would detract from logistics supportability.

(2) Logistics Supportability and Readiness Requirements. FOPS must use standard AF supportability concepts and systems.

c. Critical Systems Characteristics.

(1) Critical systems characteristics are as follows:

(a) Electronic Counter-Countermeasures (ECCM) and Wartime Reserve Modes (WARM) Requirements. Not applicable.

(b) Conventional, Initial Nuclear Weapons Effects, Nuclear, Biological, and Chemical Survivability.

1. FOPS must be capable of fulfilling its function in a CB-contaminated environment with no degradation.

2. FOPS must not be effected by chemicals and vapors normally present as a result of air base operations; e.g., gasoline, JP-8, engine oil, hydraulic fluid, ammonia, and paint thinner.

(c) Electromagnetic Compatibility and Frequency Spectrum Assignment. Not applicable.

(d) Safety Parameters.

1. FOPS must be safe to operate, store, and maintain throughout its life cycle.

2. FOPS must not present a hazard to aircraft or aircrews operating from or near the base or installation.

3. FOPS must improve on the protection levels provided by current portable shelters.

4. FOPS will be fire retardant or fire resistant. Shelter material must not produce life threatening levels of toxic fumes when burning or melting.

5. A hazard analysis will be conducted IAW MIL-STD 882B and MIL-STD 1472D.

(2) Security. Owner/user security applies IAW AFR 125-37.

(a) System Threat Assessment Report (STAR). Not applicable.

(b) Preliminary System Security Concept. Not applicable.

(c) Preproduction Security Plan. Not applicable.

(d) Operational Security Plan. Owner/user security applies IAW AFR 125-37.

(e) Protective Measures. IAW AFR 125-37. Also, shelters intended to house classified information processors should be designed to provide a minimum of 50 decibel attenuation.

(3) Electronic Counter-Countermeasures. Not applicable.

(4) Software Engineering. Not applicable.

5. **Integrated Logistics Support (ILS).**

a. Maintenance Planning. All components of the FOPS must be easily assembled, used, and maintained. Existing tools, test measurement and diagnostic equipment (TMDE) and/or presently approved emerging TMDE or support equipment (SE) will be used if required. Specialized tools, if required, will be supplied with the FOPS. If maintenance must be performed in contaminated areas, the FOPS must be designed to ensure ease of maintenance even when the technician is fully dressed in protective clothing to include arctic and mission oriented protective posture (MOPP)-4. FOPS should exhibit a cost effective, supportable design with emphasis on optimizing logistics resources using an ILS plan. As part of this plan, a logistics support analysis

(LSA) strategy should be formulated to develop the necessary taskings and information to ensure proper integration.

(1) Maintenance Concept.

(a) Two levels of maintenance are contemplated.

1. Maintenance, repair, and reconstitution tasks will be accomplished at the organizational level, either in garrison or in the field. Repair and/or replacement of parts will also be accomplished by civil engineering personnel deployed in the field. If required repairs exceed organizational level maintenance, depot maintenance teams will be provided by Air Force Materiel Command. Periodic inspections and preventive maintenance tasks will be acceptable to ensure structural hardness integrity. Maintenance and inspection tasks will be completed monthly by civil engineers while deployed in the field. (Maintenance tasks and schedules will be determined during the concept phase.)

2. Depot. A repair-level analysis/LSA must be performed by the contractor to help determine the optimum support concept, but, in general, if required repairs exceed organizational maintenance capabilities, depot maintenance will be required.

(b) The level of replacement will be at the component level.

(c) Organizational level maintenance must be such that it can be performed by civil engineering personnel with minimal specialized training and using common tools.

(d) Peacetime inspection will be by periodic erection and striking of shelters to demonstrate/verify operational status.

(2) Maintenance Requirements for On and Off-Equipment Maintenance. To be determined.

(3) Time-Phased Depot Requirements. To be determined.

(4) Organic Support Capabilities. To be determined.

(5) Depot Tasks and Capabilities Required. To be determined.

b. Support Equipment.

(1) Standard Support Equipment. The need for SE must be minimized. If SE is required, it must be designed so that it can be maintained using, to the maximum extent possible, existing test equipment already available in the DOD inventory.

(2) Depot Level Support Equipment. To be determined.

(3) Test and Fault Isolation Capabilities. If new test and SE is required, it must be of the minimum size, weight, and complexity needed to verify system performance within specified limits and unambiguously isolate malfunctions.

c. Human Systems Integration.

(1) Operational and Maintenance Training Concept.

(a) Initial system training for ATC instructors will be provided by the contractor during developmental testing and evaluation (DT&E) and initial operational testing and evaluation (IOT&E). HQ ATC will include instruction on the inspection, maintenance, and use of the system in the appropriate courses of 552XO and 552X2, civil engineer technical training.

(b) System repair will be taught in the same manner in the appropriate technical training courses.

(c) Air Force Civil Engineering Support Agency, will help develop the system operator training package for use at the base level where certain civil engineering specialty skills will require operator training on the FOPS.

(d) Training Methodology. To be determined.

(e) Additional manpower to support the FOPS will not be required.

(f) Operational equipment will be used for training.

(2) Human Performance/Human-In-Loop Issues.

(a) Using Command.

1. Manpower, Personnel, Training, Safety, Human Factors Engineering, and Health Hazards Constraints.

a. IAW AFR 800-16, MIL-STD-1472D, and MIL-STD-882B, a system safety analysis is required as part of the development effort to ensure all critical tasks associated with the FOPS can be performed by all personnel. Particular attention should be given to a preliminary hazard analysis and an operational and support hazard analysis. A human performance/decision-making process analysis will be developed from MIL-STD-46855B.

b. FOPS must not present undesirable or uncontrolled ergonomic hazards to personnel nor will it create any hazards from special materials used in its construction.

2. Maintenance and Training Concepts. As previously described.

(b) Supporting Command.

1. Manpower Requirements for Depot Maintenance, Engineering, and Materiel Management. Not required.

2. Depot Training Requirements. To be determined.

(3) Participating Command Manpower Requirements. Additional manpower not required.

(4) Training and Training Support.

(a) Operational and Maintenance Training Tasks. To be determined.

(b) Training Methodology. To be determined.

(c) Training Support for Required Operational Capabilities and Maintenance Requirements. To be determined.

(d) Airspace and Range Training Requirements. Not applicable.

d. Computer Resources. Not applicable.

e. Other Logistics Considerations.

(1) Supply Support.

(a) The FOPS must not require special storage or storage equipment.

(b) Equipment and subcomponent spares identified in the repair-level analysis must be obtained and stocked at the appropriate levels as part of the contract IAW AFR 57-9. Spares provisioning will be accomplished within 90 days after FOPS passes first article acceptance testing. A support/consumable spares kit (if required) will be provided with each system (e.g., patch kits).

(c) Shipping/storage containers must be transportable in, or as part of, ISO standard containers for sealift and overland transport by rail and truck, and must be slingable.

(d) FOPS and containers must be designed to withstand the shocks induced by transport and handling IAW MIL-STD-907B.

(e) FOPS will be packaged so they will not be adversely affected by prolonged storage under any climatic conditions or exposure to CB agents.

(f) Packaging, handling, and transportation requirements must be developed and implemented throughout the program IAW AFR 71, 75, and 76-series directives. Requirements will be consistent with the program schedule and interfaced with other ILS elements.

(g) Preservation, packing, and packaging for system components, spare parts, and SE peculiar to the FOPS must be designed and developed IAW MIL-P-9024G and MIL-STD-1367 to provide the degree of protection and handling provisions necessary based on the characteristics of the item, its source, destination, storage, and mode of transportation. The parts, components, and equipment common to the system should use preservation, packaging, and packing requirements currently in use by DOD. Preparation and approval of packaging and transportation data will be IAW DI-L-3327A and DI-L-3339.

(2) Technical Data.

(a) Technical orders will be developed IAW AFR 8-2 and cover the system installation, operation, maintenance, and inspection. These manuals will be written to a reading grade level of 7.8 (AFSC 6123.70) IAW MIL-STD-1752. These technical manuals must be fully validated by the contractor and verified by the Air Force during initial operational test and evaluation.

(b) Level III design drawings will be provided for each shelter and shelter subsystem.

(3) Facilities and Land. During normal readiness, the FOPS will be stored in existing supply and open storage warehouses.

(4) Logistics Support Analysis. To be determined.

(5) Hazardous Materials. FOPS Design and construction will minimize the need for and use of hazardous materials in the system's production and operation. If hazardous materials are used, adequate procedures and equipment will be included with FOPS to carry out disposal.

(6) Computer-aided Acquisition Logistics Support. To be determined.

(7) Supporting Command Requirements. To be determined.

6. **Infrastructure Support and Interoperability.**

a. Command, Control, Communications, and Intelligence. Not applicable.

b. Transportation and Basing.

(1) FOPS must be sufficiently rugged or adaptable to standard ISO shipping containers/racks to prevent damage to shelter/463L rail system during air, sea, truck, and rail

movement; compatible with the 463L pallet system; and capable of movement by theater distribution systems. Gross weight is limited to 10,000 lbs per pallet to permit offloading and site handling on unimproved terrain with all terrain forklifts.

(2) Containers must be designed for outside storage and be compatible with current materiel handling equipment, and must be airliftable on C-5, C-141, C-17, and C-130 aircraft. The primary mode of transport will be by air.

(3) SOUTHCOM uses a limited number of C-27 aircraft as a primary means of equipment transport; therefore, solution sets to shelter packaging and shipping to meet the C-27 configuration will be considered for limited quantities of shelters.

(4) The FOPS will be used at all bases and operating locations requiring temporary, portable shelters.

c. Standardization, Interoperability, and Commonality.

(1) To the maximum extent economically feasible, the FOPS design will emphasize modularity, standardization, and interchangeability of components and parts. FOPS will be compatible with current shelters under development, including all systems with which it must interface. Only minor modifications to existing systems should be required to achieve this capa bility.

(2) FOPS will be interoperable with Army, Navy, and allied equipment, procedures, and tactics. FOPS development will be coordinated with USANRDEC, NCEL, JOCOTAS, and USMC/MCRDAC. Close attention should be paid to adhering to equipment specifications and procedures outlined in international standardization agreements (e.g., NATO STANAGs, Quadripartite Agreement QSTAGs, Air Standardization Coordination Committee Advisory Publications).

(3) To the maximum extent possible, FOPS will use standardized quick disconnect structural and utility connections. Medical shelter utility connections will ensure compatibility with medical equipment requirements. FOPS will incorporate passageways enabling the shelters to be multiplexed with existing shelters such as TEMPER and ISO-standard tactical shelters.

(4) FOPS components will be interchangeable with existing portable shelter equipment to the maximum extent economically feasible. FOPS design standardization and modularity will accommodate new technologies in materials and material fabrication methods to enhance replacement part procurement.

(5) This requirement may be applicable to other DOD services.

(6) All electrical systems must operate on standard, nominal 3-phase power of 120/208/240 VAC, 50/60 Hertz.

d. Mapping, Charting, and Geodesy Support. Not applicable.

e. Environmental Support. Not applicable.

7. **Force Structure.** The new family of shelters will replace the Air Force inventory of bare base shelters as required. Current authorization levels for bare base shelters are identified in Tables of Allowance 157, Harvest Bare; 158, Harvest Falcon; and 159, Harvest Eagle. These authorization levels serve as a baseline to establish force structure.

8. **Schedule Considerations.**

a. Initial Operational Capability/Full Operational Capability (IOC/FOC) Actions. To be determined.

b. Required IOC Dates/Actions. To be determined.

1 Atch
Requirements Correlation Matrix

REQUIREMENTS CORRELATION MATRIX

PART I

As of Date:

SYSTEM CHARACTERISTICS	ORD I Thresholds	ORD I Objectives	ORD II Thresholds	ORD II Objectives	ORD III Thresholds	ORD III Objectives	Specifications	OT&E Evaluation Criteria
SYSTEM PERFORMANCE								
a Provide suitable structures for:								
(1) Billets	Yes							
(2) Command control	Yes							
(3) Admin offices/shops	Yes							
(4) Supply warehouses	Yes							
(5) Medical facilities	Yes							
(6) Aircraft maint. hangars	Yes							
(7) Kitchen feeding facilities	Yes							
(8) Shower-latrine facilities	Yes							
(9) Vehicle maintenance shops	Yes							
(10) Munitions storage facilities	Yes							
b Standardized design components		Yes						
c Improve on current shelter operation/maintenance		Yes						
d Shelter erection times:								
(1) Aircraft shelter	NMT 120 manhours	NMT 80 manhours						
(2) Personnel shelter	NMT 4 people in NMT 2 man-hours/150 sq ft of floor space	200 sq ft						

SYSTEM CHARACTERISTICS	ORD I		ORD II		ORD III			OT&E
	Thresholds	Objectives	Thresholds	Objectives	Thresholds	Objectives	Specifications	Evaluation Criteria
e. Shelters erectable by personnel wearing chem/artic clothing	Yes							
f. Protection level	Splinter	Semi-hard protection upgrade kits						
g. Chem/bio protection	Shelter construction or upgrade kits							
h. Fully decontaminable	Yes							
i. Compatible with CCD technology	Yes							
j. Visual image intensification blackout		w/O liner or power outage						
k. EMI RFI protection		Electric equipment shelters						
l. Vent fumes/smoke/steam/heat	Yes							
m. Interface w/utilities	Yes							
n. Electric outlets	Mod kits	Built-in						
o. Lighting packages	Yes							
p. HVAC	Compatible w/standard systems	Built-in						
q. Solar screens/insulation	Yes							
r. Operational environment								
(1) Worldwide	Yes							
(2) Field conditions	Yes							

SYSTEM CHARACTERISTICS	ORD I Thresholds	ORD I Objectives	ORD II Thresholds	ORD II Objectives	ORD III Thresholds	ORD III Objectives	Specifications	OT&E Evaluation Criteria
(3) Snow load	Support/ shed 10 lbs/ sq ft							
(4) Solar load	Withstand 205°F. w/no permanent deformation							
(5) Ultraviolet	Withstand w/o degradation							
(6) Environmental requirements	IAW MIL-STD-907B, sec.5.2. 5.3							
(7) Climate adaptation kits	Yes							
s. Withstand winds	Sustained-80mph/Gusts-100mph							
t. Flooring	Suitable/ expedient	Rigid floors: hinged doors						
u. Storage containers	Provide environ: movement protection							
v. Repair kits	Yes							
w. Fastening systems	Simple, quick disconnect							
x. Hinges/pins/fasteners components	Off-the-shelf							
y. Corrosion prevention	IAW MIL-STD-808A							
z. Lightweight/compact		Yes						
aa. Anchoring kits	Yes							
2. LOGISTICS AND READINESS								
a. Assembly/disassembly cycles:								

SYSTEM CHARACTERISTICS	ORD I Thresholds	ORD I Objectives	ORD II Thresholds	ORD II Objectives	ORD III Thresholds	ORD III Objectives	Specifications	OT&E Evaluation Criteria
(1) Small shelters	12 cycles over 20 years	26 cycles over 20 years						
(2) Large shelters	12 cycles over 20 years	20 cycles over 20 years						
b. Continual use life	At least one year continual use	At least two years continual use						
c. Warehousing	At least 5 years w minimum insp/maint	10 years						
d. Shelf life	20 years							
e. Operation after extended storage	W NMT minor field maint							
3 CRITICAL SYSTEMS CHARACTERISTICS								
a. Chemical/biological environment	Yes							
b. Affected by chemicals, vapors, e.g., oil, gas, ammonia, JP-8	No							
c. Safe to operate/store, maintain	Yes							
d. Hazard to aircraft/aircrew	No							
e. Improve protection levels of current shelters	Yes							
f. Fire retardant/resistant	Yes							
g. Hazard analysis	IAW MIL-STD 882B and 14720							
h. Attenuation for classified processing facilities	50db							
4. MAINTENANCE PLANNING								

SYSTEM CHARACTERISTICS	ORD I Thresholds	ORD I Objectives	ORD II Thresholds	ORD II Objectives	ORD III Thresholds	ORD III Objectives	Specifications	OT&E Evaluation Criteria
a. Easily assembled/used/maintained	Yes							
b. Maintenance levels								
(1) Organizational	Yes							
(Field-In-Garrison)								
(2) Depot		TBD						
c. Replacement level	Component							
d. Organizational maintenance	Minimum training common tools							
5. SUPPORT EQUIPMENT								
a. Use existing DOD test equipment	Yes							
b. Built-in test equip	Yes							
c. New test equipment		Minimize						
d. Test/fault isolation		Verify performance/isolate malfunctions						
6. HUMAN SYSTEMS INTEGRATION								
a. Initial system training		Contractor						
b. Human factors engineering program	Yes							
c. System safety analysis IAW AFR 800-16, MIL-STD-1472D, and MIL-STD-882B	Yes							
7. OTHER LOGISTICS CONSIDERATIONS								
a. Equipment/spares acquisition/stockage	IAW AFR 57-9							

SYSTEM CHARACTERISTICS	ORD I Thresholds	ORD I Objectives	ORD II Thresholds	ORD II Objectives	ORD III Thresholds	ORD III Objectives	Specifications	OT&E Evaluation Criteria
b. Standard DOD packing/packaging/preservation	IAW MIL-STD 907B and 1367, MIL-P-9024G, DI-L-3327A and 3339, and AFR 71, 75, and 76-series regs							
c. Technical orders								
(1) IAW AFR 8-2 and MIL-STD-1752	Yes							
(2) Reading level		Grade 7.8						
d. Level III drawings	Yes							
e. Hazardous materials use		Minimize						
8. TRANSPORTATION AND BASING								
a. Theater distro systems	Yes							
b. Air land/sea/transportable	Yes							
c. Compatible with 463L system	Yes							
d. C-27 movement capability		Yes						
9. STANDARDIZATION, INTEROPERABILITY, AND COMMONALITY								
a. Design emphasis		Modular/standardized/interchangeable components						
b. Structural/utility connections		Quick disconnect						
c. Compatibility with existing shelter equipment		Maximized						
d. Interoperable with Army/Navy/allied equipment/procedures/tactics	Yes							
e. Use common power sources	Yes							

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AFSOC/XP	(3)	
AFSOC/LG	(3)	6
LANGLEY AFB, VA 23665-5575		
HQ ACC/HO	(1)	1
KELLY AFB, TX 78241-5260		
SA-ALC/FMX	(5)	5
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AUL/LSE	(1)	1
McCLELLAN AFB, CA 95652-5260		
SM-ALC/FMP	(5)	5
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AGMC/XPR	(1)	1
NORTON AFB, CA 92409-7001		
HQ AFSA/SESD	(2)	2
WASH, DC 20330-5057		
HQ USAF/XOXXI	(1)	1
KIRTLAND AFB, NM 87117-7001		
DET 1 AFSA/SNA	(1)	1
PETERSON AFB, CO 80914-5000		
HQ AFSPACECOM/XPR	(3)	
HQ AFSPACECOM/DE	(2)	5
RANDOLPH AFB, TX 78150-6001		
HQ AFMPC/DPMYF	(1)	1
RANDOLPH AFB, TX 78150-5001		
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TYNDALL AFB, TX 32403-6001		
HQ AFCESA/DX	(3)	
HQ AFCESA/RA	(3)	
HQ AFCESA/DF	(3)	
HQ AFCESA/EN	(2)	11
BROOKS AFB, TX 78235-5301		
AL/XPX	(2)	2
SAN ANTONIO, TX 78243-5000		
HQ AFIC/XP	(7)	
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APPENDIX C

SHELTER REQUIREMENTS SURVEY

A. INTRODUCTION

On 29 May 1992, a follow-up survey was mailed to each of the forty Air Force personnel who attended the Portable Shelter Requirements Working Group (RWG) Meeting held at Tyndall AFB during the week of 10 February 1992. The purpose of the survey was to collect additional information on Air Force needs for the next generation of shelters and to prioritize the conflicting design objectives specified in the draft *Portable Shelter Operational Requirements Document* (ORD). The information on shelter priorities is used as an input to the ASEM shelter evaluation model.

As of 24 July 1992, twenty-one responses to the survey had been received. A statistical summary of the survey results is provided in the following three sections. First, we examine the responses to the individual questions. Next, we summarize the responses given by respondents who have similar types of involvement with portable shelters. Finally, we briefly investigate the influence of some additional classification variables on the shelter objective weights.

The results of this survey should not be taken as representative of the entire Air Force portable shelter community. No attempt has been made to scientifically select the sample group, and no attempt has been made to weight the response to reflect the size or influence of any group or organization. The survey was simply sent to all AF personnel on the attendance list of the Portable Shelter RWG minutes. The individual response rate was approximately 50 *percent*; however, responses were obtained from nearly all of the organizations represented at the RWG meeting.

B. SUMMARY OF OVERALL RESPONSES TO EACH SURVEY QUESTION

1. *Question 1*: Respondents' Involvement with Portable Shelters

Based on the explanations given for the "Other" responses to this question, the four specific categories listed in the survey were supplemented with two additional categories: (5) shelter management (including program management, shelter acquisition, and shelter planning); and (6) shelter research, development, testing, and evaluation (RDT&E). Thus, the six classes of shelter involvement to be considered are: (1) owner/user, (2) depot (maintenance and storage), (3) transportation, (4) assembly (and disassembly), (5) management, and (6) RDT&E.

Figure C-1 summarizes the primary and secondary shelter involvements of the survey respondents. For each of the six classifications, at least five survey respondents claimed either a primary or secondary role. One-half or more of the respondents indicated a familiarity

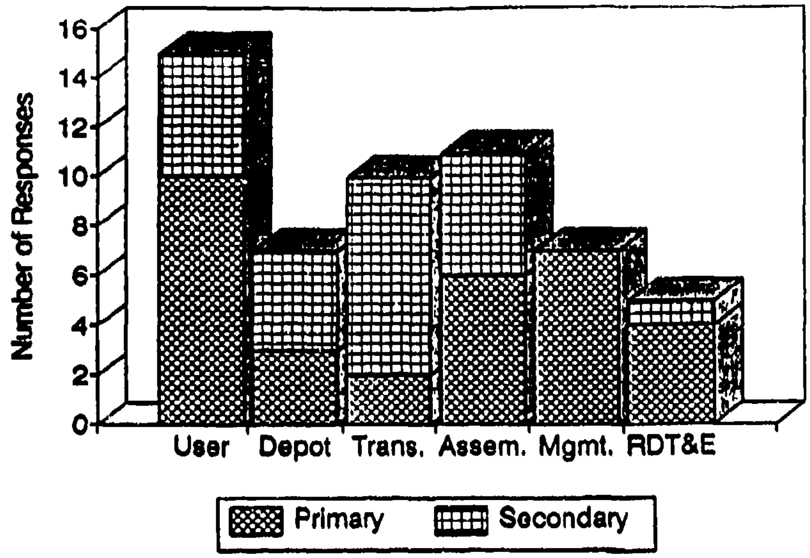


Figure C-1. Respondents' Involvement with Portable Shelters.

with the owner/user, transportation, and assembly roles. In addition, one-third of the respondents stated a primary involvement that fit into the shelter management, acquisition, and planning category.

2. *Question 2*: Causes of Shelter Wear and Tear

The responses to the second question are summarized in Figure C-2. On average, about half of shelter deterioration was thought to occur while the shelters are in use, approximately one-fourth of damage occurs during erection and striking, and the remaining one-fourth of damage is split between transport damage and deterioration during storage. The survey question was not specific about the shelter type, deployment conditions, etc., and the familiarity of the respondents with shelter damage modes varied. Therefore, it is not surprising that there was a significant amount of scatter in the responses (as indicated by the standard deviations listed in Figure C-2). The relative variabilities in responses for both storage and transport damage are particularly large.

3. *Question 3*: Rankings of Shelter Threats

The perceived likelihoods of six possible classes of shelter threats are summarized in Figure C-3. The most distinctive feature of this survey question was the possibility of negligible overall threat. Since negligible threat represents an extreme case, it is not surprising that all of the respondents ranked it as either the most likely or the least likely of the six possibilities (*i.e.*, either first or sixth). However, the breakdown between the two extremes is informative. Negligible threat was rated least likely by 86 *percent* of the respondents while 14 *percent* of the respondents ranked it as most likely. Of the five other threat scenarios, the

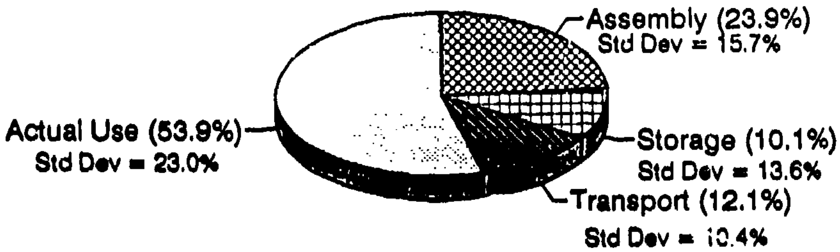


Figure C-2. Estimated Sources of Shelter Wear and Tear.

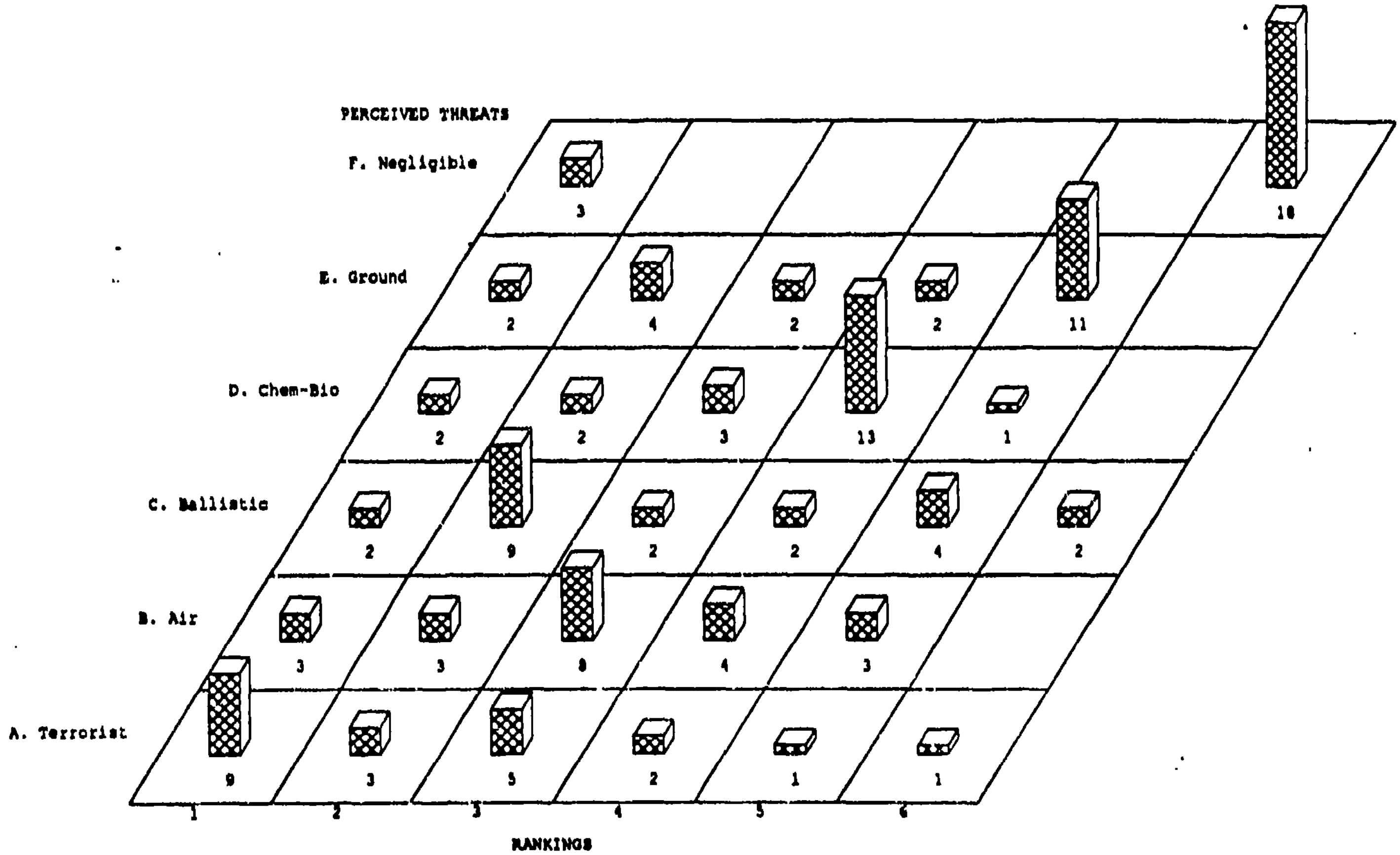


Figure C-3. Frequency Block Chart of Perceived Shelter Threat Rankings. (Note: Due to an incomplete response on one survey, the number of responses in three rows and three columns of the chart do not sum to 21.)

terrorist/commando threat was viewed, on average, to be the most likely (receiving 43 *percent* of the first place votes). In decreasing order of likelihood, the average perception of the remaining threats was: air threat, theater ballistic missile, chemical-biological (air or surface launched), and ground threat. However, there was not a clear consensus on the ranking of these four threats.

4. *Question 4:* Weighting of Major Shelter Objectives

The relative weights given to the six major shelter objectives are illustrated in Figure C-4 (small shelters) and Figure C-5 (large shelters). A one-way multi-variate analysis of variance indicated that the differences in the prioritizations for small *vs.* large shelters are statistically insignificant. That is, no clear trends were identified when comparing the small shelter priorities to the large shelter priorities. As a result, the small and large shelter weights have been combined into a single set of overall shelter objective weights. The overall shelter weights are illustrated in Figure C-6.

None of the major shelter objectives dominates or is dominated by the other objectives. When averaged over all respondents, the ratio of the largest to the smallest objective weights (*i.e.*, functionality/operability *vs.* cost) is less than a factor of two. In general, the standard deviations obtained for each of the objective weights are approximately one-half of the corresponding average values. The lone exception is hardness which has a coefficient of variation (COV = standard deviation/mean) of 80 *percent* compared to COVs of 40 to 60 *percent* for the other five objectives. In other words, there is a significant level of uncertainty regarding the importance of shelter hardness against conventional and chemical-biological weapons effects. In fact, the weights given by the survey respondents for shelter hardening ranged from a low of 2 *percent* to a high of 40 *percent*.

If we combine transportability and rapid assembly into a single higher level objective called shelter mobility and if we also combine reliability, maintainability, functionality, and operability into a single higher level objective called shelter performance, then the average weights for the four highest level objectives are as shown in Figure C-7. Viewed in this manner, mobility and performance are approximately equally weighted, and each receives approximately three times the weight of either the hardness or cost objectives.

5. *Question 5*: Shelter Hardening Approaches.

Since shelter hardness severely conflicts with the mobility and cost objectives, it is important to consider shelter design concepts that may mitigate this conflict. One such approach is to provide a basic design that emphasizes mobility and low cost yet ensures that the hardness of the shelter can be rapidly upgraded in the field, if necessary. The drawbacks of this approach are logistical complexity (additional parts are required to install the upgrades) and the dependence on adequate warning to allow time for installing the hardness upgrades. Given these issues, the purpose of this question was to discern any preferences towards integral shelter hardness vs. upgradeable shelter hardness. An intermediate level of hardening called "partial integral hardness" was also suggested as a possible alternative in which some intermediate level of integral hardness is provided with the shelter but additional upgrades are needed to fully achieve the desired hardness.

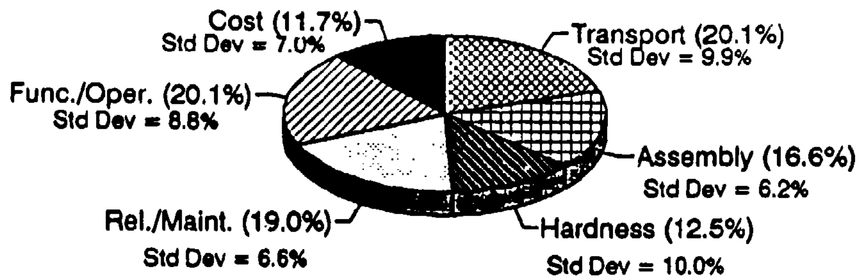


Figure C-4. Small Shelter Objective Weights.

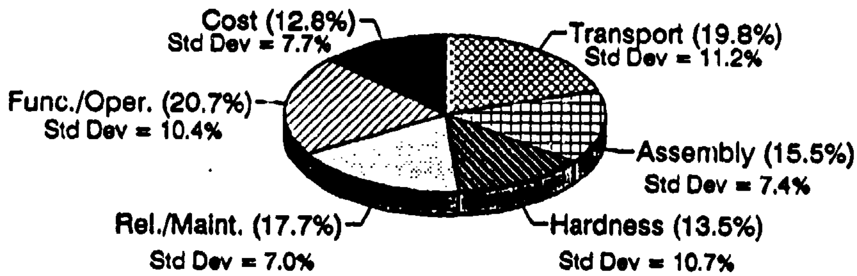


Figure C-5. Large Shelter Objective Weights.

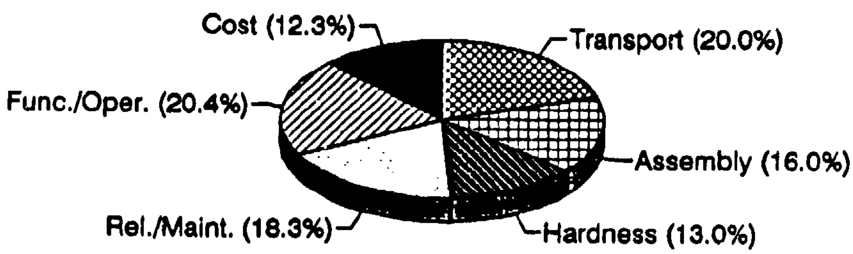


Figure C-6. Overall Shelter Objective Weights (Average of Small and Large Shelter Responses).

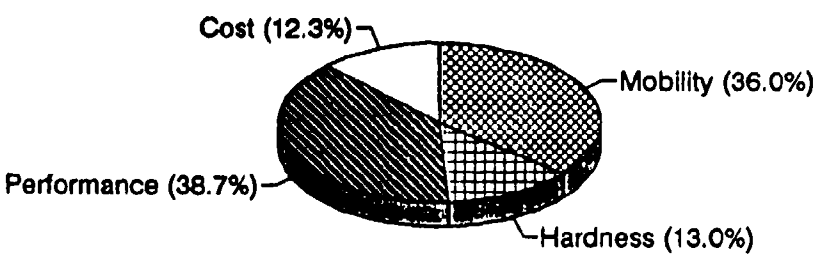


Figure C-7. Overall Shelter Objective Weights Based on Four Major Objectives.

The survey results for fragment and small arms threats are shown using a 3-D bar chart in Figure C-8. The responses are almost uniformly spread over the range of possibilities. Because it received only three 3^{rd} place votes, the partial integral hardness option was most favored on average. The responses for integral hardness were mostly split between most favored and least favored alternative, and no clear preference can be discerned for the upgradeable hardness approach.

The results for chemical-biological hardening in Figure C-9 are quite similar to the results for fragment and small arms. The main difference is in integral hardening. For chemical-biological threats, a clear majority of the respondents listed integral hardening as the least-favored approach.

The results from Question 5 indicate that there is no one most-preferred hardening approach at this time. Several respondents suggested that this question be revisited at a future date after more results from the current research programs become available.

C. SUMMARY OF SURVEY RESPONSES BROKEN DOWN BY SHELTER INVOLVEMENT.

Table 1 summarizes the average responses to questions two, three, and four of the survey according to the types of shelter involvement noted by each respondent. Respondents were included in each of the groups for which they indicated either a primary or secondary role (see Section B.1). For the purposes of the following comparisons, the small and large shelter responses to Question 4 have been combined into an overall shelter objective weights category (see Section B.4). The numerical values listed in Table C-1 for question three are the average rankings given to each of the six possible threats. Key results for each group are discussed in the following paragraphs.

1. *Group 1*: Owner/Users

Fifteen respondents checked Owner/User as a primary or secondary shelter involvement. Compared to the overall sample group, the Owner/User group attributed more shelter damage to actual use as opposed to storage, transport, or assembly. The Owner/Users attributed 65 *percent* of shelter deterioration to shelter use compared to 53 *percent* for the overall group. The threat rankings given by the Owner/User respondents were quite similar to the overall rankings; however, the Owner/Users were more likely to list terrorist/commando as the most likely threat (an average ranking of 1.8 *vs.* 2.3 for the entire group). All nine of the first place votes for the terrorist/commando threat came from Owner/Users. When weighting the six shelter objectives, the Owner/Users were fairly consistent with the overall sample group. In general though, Owner/Users tend to put increased weight on hardness and functionality/operability and less emphasis on the cost and transportability objectives. In fact, the Owner/User group placed more priority on functionality/operability than any other group, and it placed less priority on cost than any other group.

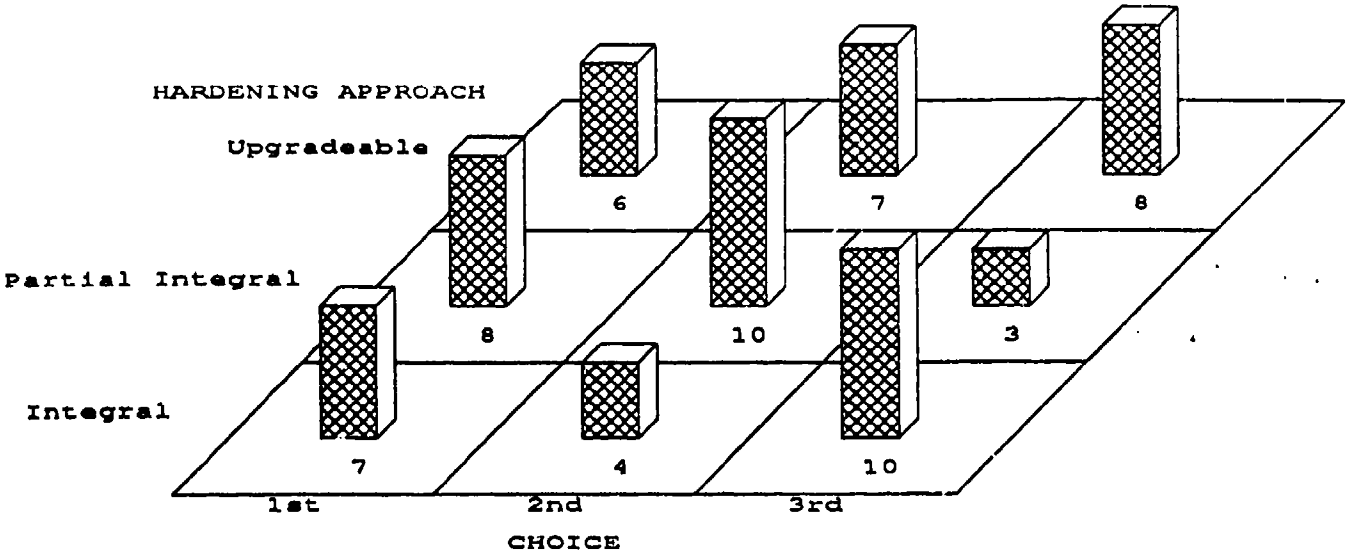


Figure C-8. Frequency Block Chart of Hardening Approach Rankings for Fragment/Small Arms Threat.

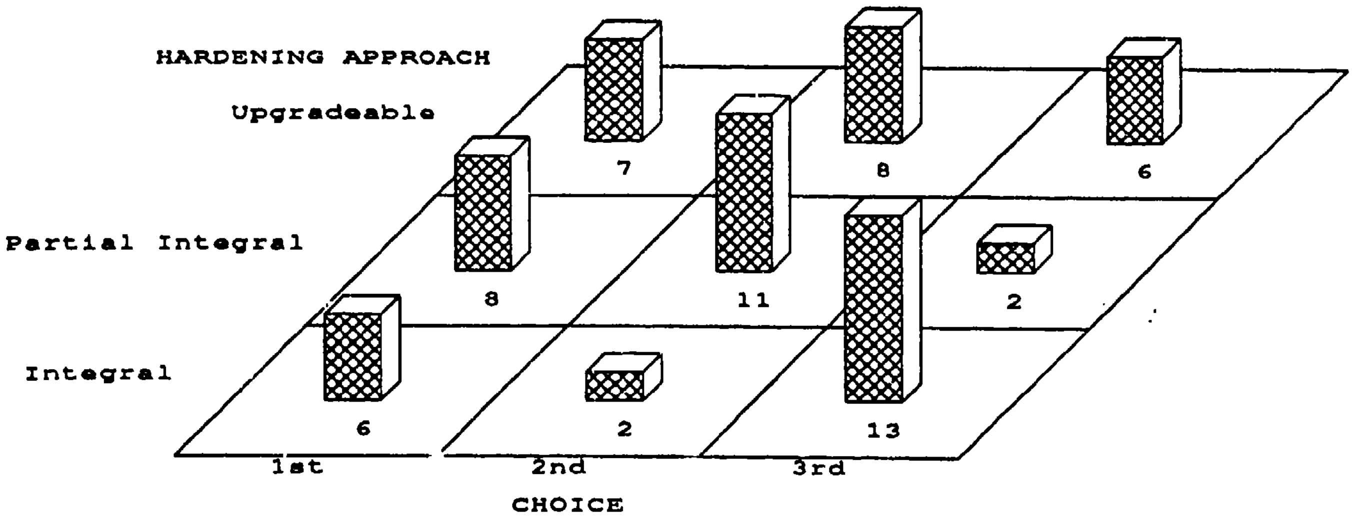


Figure C-9. Frequency Block Chart of Hardening Approach Rankings for Chemical-Biological Threats.

TABLE C-1. SUMMARY OF SURVEY RESULTS BY SHELTER INVOLVEMENT GROUP[a]

Survey Question/Response		All	Shelter Involvement Group					
			User	Depot	Trans.	Assem.	Mgmt.	RDT&E
Q2.	Storage	10.1	6.2	[illegible]	7.1	6.7	7.4	22.5
	Transport	12.1	9.1	[illegible]	10.7	9.3	15.4	16.3
	Assembly	23.9	19.6	27.5	18.6	[illegible]	34.3	26.3
	Actual Use	53.9	65.1	60.0	63.6	68.4	42.9	[illegible]
Q3.	Air	3.0	3.1	[illegible]	3.5	3.1	3.6	2.8
	Ground	3.8	3.7	4.1	3.8	3.6	4.4	[illegible]
	Terrorist	2.3	1.8	2.0	1.7	1.5	2.7	[illegible]
	Ballistic	3.1	3.1	3.0	2.9	[illegible]	2.9	3.2
	Chem-Bio	3.4	3.7	3.4	3.6	[illegible]	2.9	3.4
	Negligible	5.3	[illegible]	4.6	5.5	5.5	4.6	4.0
Q4.	Transport	20.0	18.5	19.0	[illegible]	19.0	23.6	27.5
	Assembly	16.0	15.6	14.8	16.6	15.0	16.8	[illegible]
	Hardness	13.0	14.3	15.4	16.9	15.7	[illegible]	16.5
	Rel./Maint.	18.3	18.9	17.3	17.7	19.0	16.8	[illegible]
	Func./Oper.	20.4	22.6	19.8	19.6	19.5	[illegible]	18.1
	Cost	12.3	[illegible]	14.0	11.6	11.8	13.1	11.0

a [light shading] = Group that views the current attribute most strongly.

[dark shading] = Group that views the current attribute least strongly.

2 *Group 2*: Depot (Maintenance and Storage)

Respondents in the Depot group were much less likely to attribute shelter deterioration to the storage mode (4.2 *percent* *vs*. 10.1 *percent* for the overall group). This group was also less likely to rank negligible overall threat as least likely and tended to perceive less of an air threat to portable shelters. For the weighting of shelter objectives, the Depot group placed more emphasis on hardness and cost than the overall group (about 2 percentage points more in both cases). The Depot group gave cost the highest weighting of any of the groups. Interestingly, the Depot group gave slightly less weight to the other objectives (including reliability/maintainability) than the overall group.

3. *Group 3*: Transportation

The Transportation group's ratings of shelter damage sources are quite similar to those of the Owner/User group. Their average estimate of transportation related damage quite near to the mean estimate of the overall group. The threat rankings of the Transportation group are also in-line with the overall group rankings. The major differences in threat perception are a higher likelihood of terrorist/commando threat (1.7 *vs*. 2.3) and a lower expectation of an air threat (3.5 *vs*. 3.0). Surprisingly, the Transportation group attached *less* weight to the transportabilty objective than any of the other groups, and, at the same time, they gave more weight to the hardness objective than any of the other groups. The other weights given by this group were all within 1 percentage point of the overall group weights.

4. *Group 4:* Assembly/Disassembly

The Assembly respondents produced the lowest estimate of shelter damage during assembly and the highest estimate of damage during actual use. The Assembly group also tended to rate the terrorist/commando threats and ground threats higher than any other group while rating the ballistic missile and chemical-biological threats lower than any other group. The shelter objective weights given by this group tended to be in-line with the overall weights. However, the Assembly group's hardness weight was 2.7 points *above* the overall average, and their reliability/maintainability weight was the highest of any of the groups (although only 0.7 points above the overall average).

5. *Group 5*: Management, Acquisition, and Planning

Compared to the overall group estimates, the Management group's estimates on shelter wear and tear tended to be much less a result of shelter use and more due to the transportation and assembly/disassembly phases. On question number three, the Management group ranked the air, ground, and terrorist/commando threats lower than the overall group (by about one-half of a position in the ranks on average) and the remaining three threats higher than the overall group. For the shelter objective weights, the Managers gave relatively high weights to rapid assembly, transportability, and cost in comparison to the overall group, but they placed less emphasis on hardness and functionality/operability than any of the other groups.

6. *Group 6*: Research, Development, Testing, and Evaluation (RDT&E)

Many of the mean responses given by the RDT&E group were the highest or lowest values among the six groups. There are at least two possible explanations for the extreme results: (1) the RDT&E group has the smallest number of respondents (*i.e.*, the average group responses can be significantly influenced by the responses of one or two individuals); and (2) the RDT&E respondents may have a significantly different perspective on shelter performance and shelter needs. The RDT&E group had the highest weights or ranks on: storage and transport deterioration in question two, the air and negligible overall threats in question three, and the transportation objective in question four. An additional highly weighted RDT&E objective is shelter hardness (16.5 *percent vs.* 13.0 *percent* for the overall group). Low weights or ranks were assigned by the RDT&E group to deterioration during shelter use (question two), the ground and terrorist/commando threats (question three), and the rapid assembly and reliability/maintainability shelter objectives (question four).

7. Summary of Shelter Involvement Group Analysis

Although the survey results indicate that there are significant differences in some of the group preferences, the variations in mean responses by group are not as clear as might have been expected. In fact, some of the trends are counter-intuitive (*e.g.*, the Transportation group gave less weight to the transportability objective than any of the other groups and at the same time gave more weight to the hardness objective than any of the other groups). The lack of clear, explicable trends may be due to the small sample sizes in the individual groups, the fact that many of respondents indicated familiarity with two or more of the roles (*i.e.*, the groups are not mutually exclusive), and other factors.

If we only include respondents that claim a primary level of involvement in each group (*i.e.*, the "experts" within each area), a new set of group results can be computed. For completeness, these results are summarized in Table C-2. Although most of the numerical values in Table C-2 differ from the results in Table C-1, we note that removing respondents who claim only a secondary role in the groupings does not significantly change the ranges of mean responses. In many cases, the highest and lowest values for a particular shelter attribute are generated by the same groups in both tables.

D. ADDITIONAL CLASSIFICATION VARIABLES THAT INFLUENCE THE SHELTER OBJECTIVE WEIGHTS

While looking for trends in the survey results, we considered several additional response classification variables. For example, in Section B.4, we mentioned that shelter size did not significantly influence the average weights given to the six major shelter objectives. Among the other factors we considered, two were found to have significant influences on the weights given to the shelter objectives: (1) the rank of the respondent, and (2) the type of shelter associated with the respondent's organization.

1. Respondent Rank

The survey respondents fell into five ranks: LTC, MAJ, CAPT, SGT, and Civilian. Based on the results of a multi-variate analysis of variance (MANOVA), rank was found to significantly influence the weights assigned to the transportability and cost objectives. Table C-3 summarizes the mean weights given to these two objectives according to respondent rank. The results indicate that higher ranking respondents tended to give less weight to transportability. Although there are significant differences in the weights given to the shelter cost objective, there does not appear to be a trend with ascending or descending rank.

2. Shelter Type

The second significant response variable is shelter type. One of four possible shelter types was associated with each of the respondents: general purpose shelters (*e.g.*, bare base), transportable collective protection shelters used for CBW protection, C3/Electronics

TABLE C-2. SUMMARY OF SURVEY RESULTS BY PRIMARY SHELTER INVOLVEMENT GROUP.[a]

Survey Question/Response		All	Shelter Involvement Group: User	Depot	Trans.	Assem.	Mgmt.	RDT&E
Q2.	Storage	10.1	7.5	5.0	7.5	[illegible]	7.4	28.3
	Transport	12.1	9.9	10.0	17.5	[illegible]	15.4	20.0
	Assembly	23.9	15.6	15.0	17.5	[illegible]	34.3	28.3
	Actual Use	53.9	67.0	70.0	57.5	77.2	42.9	[illegible]
Q3.	Air	3.0	2.8	[illegible]	3.0	3.5	3.6	2.5
	Ground	3.8	3.0	4.3	3.5	4.2	4.4	[illegible]
	Terrorist	2.3	2.1	1.0	1.0	1.2	2.7	[illegible]
	Ballistic	3.1	3.2	2.0	3.0	2.3	2.9	[illegible]
	Chem-Bio	3.4	3.9	3.7	[illegible]	3.8	2.9	3.5
	Negligible	5.3	[illegible]	[illegible]	[illegible]	[illegible]	4.6	3.5
Q4.	Transport	20.0	17.8	16.3	[illegible]	19.3	23.6	28.3
	Assembly	16.0	15.1	14.7	[illegible]	5.8	16.8	15.8
	Hardness	13.0	13.1	14.2	15.0	[illegible]	11.9	12.0
	Rel./Maint.	18.3	20.6	15.5	20.0	20.1	16.8	[illegible]
	Func./Oper.	20.4	23.4	22.2	25.0	21.2	17.9	[illegible]
	Cost	12.3	[illegible]	17.2	11.3	13.2	13.1	12.2

a (light shading) = Group that views the current attribute most strongly.

(dark shading) = Group that views the current attribute least strongly.

TABLE C-3. MEAN WEIGHTS GIVEN TO THE TRANSPORTABILITY AND COST OBJECTIVES BY RESPONDENT RANK.

Objective	Overall	Rank: LTC	MAJ	CAPT	SGT	Civilian
Transport	20.0	11.4	18.0	28.1	22.0	22.5
Cost	12.3	13.1	9.5	14.3	5.8	20.0
No. Responses[a]	39	10	10	10	5	4

[a] Includes both small and large shelter responses.

shelters, and shelter equipment (*e.g.*, environmental control units). The MANOVA procedure revealed that the weights assigned to the transportability objective and, to a lesser extent, the hardness objective were related to the type of shelter the respondent was associated with. The mean weights for these objectives are shown in Table C-4. Not surprisingly, those respondents associated with CBW shelters tended to rank hardness much higher than the respondents associated with the other shelter types. Perhaps due to the need to balance many objectives, the general purpose shelter users tended to rate both transportability and hardness lower than they were rated by the overall group.

TABLE C-4. MEAN WEIGHTS GIVEN TO THE TRANSPORTABILITY AND HARDNESS OBJECTIVES BY TYPE OF SHELTER.

Objective	Overall	Shelter Type			
		GP	CBW	C3	Equip.
Transport	20.0	17.6	20.0	32.5	30.0
Hardness	13.0	11.2	22.5	18.0	10.0
No. Responses[a]	39	29	4	4	2

[a] Includes both small and large shelter responses.

5. CONCLUSIONS

Twenty-one responses to the shelter priorities survey were returned to AFCESA/RACS. The respondents represent a wide array of Air Force organizations, portable shelter types, and shelter responsibilities. As mentioned in the introduction, the results of this survey should not be taken as representative of the entire Air Force portable shelter community since no attempt was made to scientifically select the survey population. The results of this survey should be considered an informal supplement to the results of the Requirement Working Group meeting.

The primary purpose of the survey was to gather information on the relative importance of the six major shelter objectives outlined in the draft Operational Requirements Document (ORD). The overall opinion of the respondents suggests that none of the six objectives dominates the others nor is any objective completely dominated by others. The relative uniformity in shelter attribute weights indicates that the users are not willing to single-mindedly optimize one or two of the objectives at the expense of adequately addressing the other objectives. Functionality/operability and transportability were the two most strongly weighted objectives (approximately 20 *percent* each). The lowest weights were placed on cost (12 *percent*) and hardness (13 *percent*). Differences in the weightings for small *vs.* large shelters were statistically insignificant. Variations in the objective weights between various sub-groupings of survey respondents are discussed in Sections C and D.

On average, actual shelter use was thought to cause slightly more than half of all shelter wear and tear. Approximately one-fourth of shelter damage was attributed to assembly/disassembly, and the remaining one-fourth split roughly equally between the transportation and storage modes.

The most likely shelter threat category was thought to be the terrorist/commando threat. Almost half of the respondents listed this threat as number one. At the other end of the spectrum, negligible overall threat was viewed as least likely by 86 *percent* of the respondents. Air, ballistic missile, chemical-biological, and ground threats were ranked second through fifth, respectively; however, there was not a clear consensus on the rankings of these middle four threats.

There was little agreement on the hardening options for fragment/small arms and CB threats. The partial integral hardening approach was most highly regarded overall due to its low number of third place votes. The question of shelter hardening options should be reconsidered by the shelter user community when more research information is available.

APPENDIX D

ASEM CODE DESCRIPTION

The objective of the Airmobile Shelter Evaluation Methodology (ASEM) package is to evaluate airmobile shelter concepts in terms of their usefulness and intrinsic worth to the decision maker under different shelter selection scenarios. The output of this package can be classified in three different categories: (1) plots of single attribute utility curves, (2) utility contour plots as a function of any two attributes given fixed values of the remaining attributes, and (3) the overall utility of a shelter concept on a scale of 0 to 1 and additional high level quantitative measures of overall shelter performance (*i.e.*, number of worker-days required to build a bare base and number of transport planes required to deliver the shelters).

The ASEM code is programmed in the C computer language and is currently being run on an IBM-compatible personal computer using the DOS operating system. The code consists of six main modules:

1. Creation of hierarchical structure.
2. Calculation of individual utility function parameters.
3. Plotting single attribute utility functions.
4. Calculation of scaling constants.
5. Contours of overall utility after fixing all but two attributes.
6. Calculation of overall utility.

A. CREATION OF HIERARCHICAL STRUCTURE

The data structure used to define the shelter analysis hierarchy is in the form of the tree shown in Figure D-1. Each node in the tree corresponds to an objective/attribute and is characterized by a data structure denoted as structure K. Structure K stores the following information:

1. Level number (starting with 0 at the root).
2. Attribute number (no).
3. Preference number (pref_no).
4. A logical variable which takes value 0 or 1 (fix).
5. Attribute name (name).
6. Abridged name (abridged).
7. Dimension (unit).
8. Scaling constant of the attribute (k_value).
9. Forward link (s_forw).
10. Backward link (s_back).
11. Parent node link (p_link).
12. Link to structure U (u_link).
13. Link to structure DU if the attribute has discrete utility function (du_link).
14. Link to a header node from the first node of each level counting from left to right (h_link).
15. An array of links to all immediate sub-attributes (c_link [MAXCHILD]).

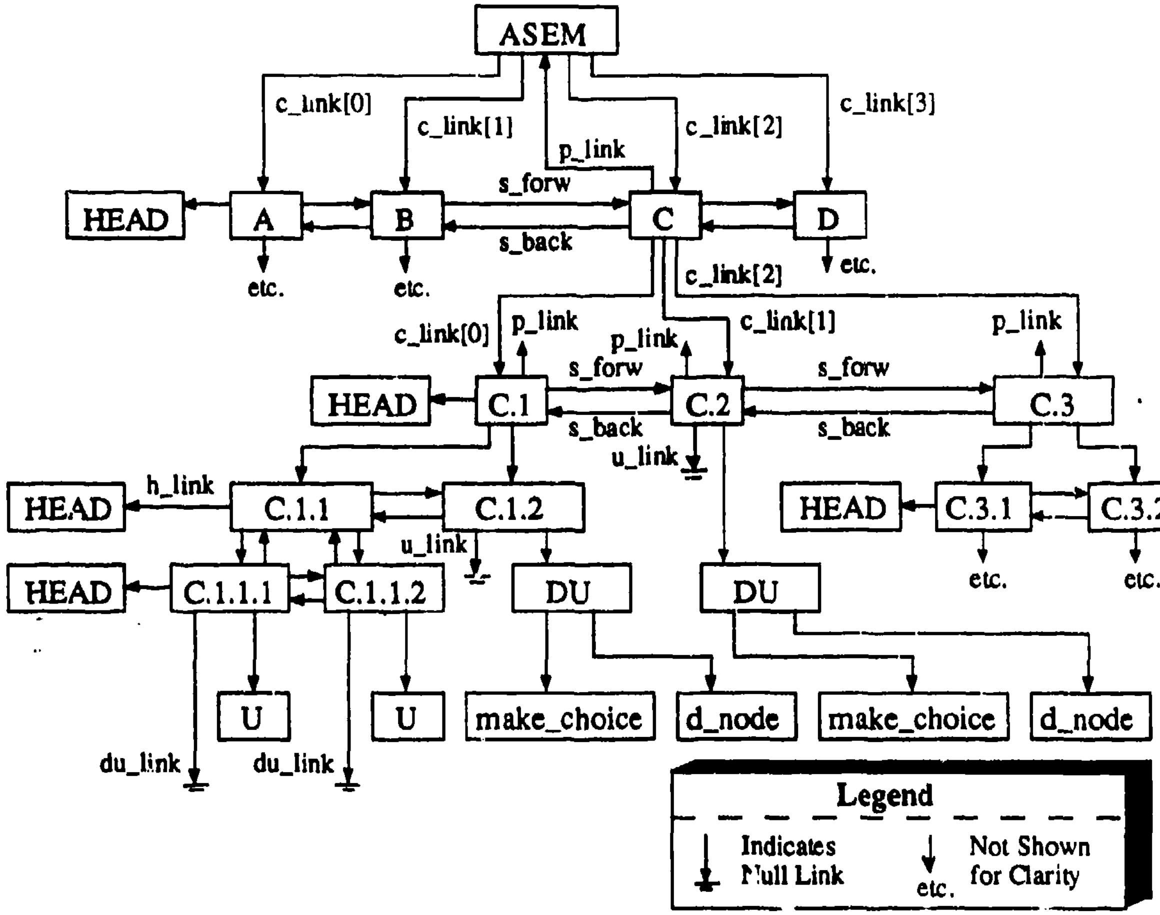


Figure D-1. ASEM Data Structure.

Structure HEAD defines the header node at each level in the hierarchy. The header node stores information related to the type of overall utility at this level (*i.e.*, additive or multiplicative). The specific information stored in HEAD is

1. An integer variable (ad_mu) which indicates whether the overall utility at this level is additive (ad_mu = 1) or multiplicative (ad_mu = 0).
2. The value of the interaction constant, if the overall utility is multiplicative (inter).
3. A link to itself (h_link).

All of the information related to the utility function of a continuous attribute is stored in the structure U as follows:

1. Utility function parameter a (a).
2. Utility function parameter b (b).
3. Risk constant r (r).
4. An integer variable (fun) that indicates the type of utility function: linear, exponential, or logarithmic (the logarithmic utility function is not currently in use).
5. Least desirable possible value of the attribute (low).

6. Best possible value of the attribute (high).
7. A link to the next node (next).

Structure DU is similar to the structure U except that it is used for discrete attributes. Structure DU stores the following information:

1. Number of possible discrete states (no_of_nodes).
2. Best discrete state (best).
3. Least desirable state (worst).
4. Utility value of a particular state (value).
5. A link to the structure D_NODE (dn_link)
6. A link to the next node of the same type (du_link).
7. A link to the structure MAKE_CHOICE which is used to flag the applicable discrete states for a given concept (ch_link).

Structure D_NODE stores the different possible states of a discrete attribute and their associated utility values. The variables in D_NODE are:

1. Discrete attribute state number (no).
2. Discrete attribute state name (name).
3. Discrete attribute abridged state name (abridged).
4. Forward link to the next discrete state (dn_forw).
5 Backward link to the previous discrete state (dn_back).

Finally, the structure MAKE_CHOICE stores the state of a discrete valued attribute for a particular shelter concept using an integer array (my_choice). If the possible discrete states of the attribute are mutually exclusive, no more than one entry is allowed in the array my_choice. For attributes with non-exclusive states, multiple features of the attribute may be found in a single concept. In the latter case, the array my_choice would have entries for each of the attribute features displayed by the concept.

Thirteen different functions are used in creating ASEM hierarchy. These functions are briefly described in the following paragraphs.

create_asem(). This function creates the root node of the hierarchy. First, the function allocates memory for a structure of type K by using the function make_k_node(). Next, it assigns links to the return values of four different functions: create_mobility(), create_cost(), create_shelter(), and create_survive(). Finally it returns a pointer to the root node.

create_mobility(). This function creates the structure of the mobility objective along with all the attributes which come below it (*i.e.*, children of mobility). Three types of structures are needed for mobility — types K, U and HEAD. The memory allocation for these structures are done by the functions make_k_node(), make_u_node(), make_h_node() respectively.

create_cost(). This function creates the structure of the cost objective. Again, make_k_node(), make_u_node(), and make_h_node are used to allocate memory for structures K, U, and HEAD respectively.

create_shelter(). This function creates the structure of the shelter performance objective. Four different type of structures, namely, K, U, DU, and HEAD are needed to create the full structure of this module. The functions make_k_node(), make_u_node(), and make_h_node() are used to create structures K, U, and HEAD. Structure DU is created by the function make_du_node(). The pointer dn_link of structure DU is assigned the return value of either the function IE_list_int() if the attribute under consideration is ergonomics or the function IE_list_mod() if the attribute is modularity.

create_survive(). This function creates the structure of the survivability objective. Using functions make_k_node(), make_u_node(), make_h_node() and make_du_node(), structures of types K, U, HEAD, and DU are created. The pointer dn_link of structure DU is assigned the return value of either the function IE_list_lb or IE_list_lm depending on whether the attribute is labor skills or local materials. The structures are linked as shown in Figure D-1.

IE_list_mod(), IE_list_int(). These two functions make lists of structures of type D_NODE which contain the different states of the attributes modularity and habitability, respectively. Each of the four functions returns a pointer to the beginning of the list.

make_k_list(), make_u_list(), make_h_list(), and make_du_list(). These four functions allocate memory for structures of types K, U, HEAD, and DU, respectively.

B. CALCULATION OF INDIVIDUAL UTILITY FUNCTION PARAMETERS

Two different classes of utility functions are available in ASEM: continuous utility functions and discrete utility functions. The procedures used to compute the utility values for continuous and discrete attributes are summarized in the following subsections.

1. Continuous Utility Functions

The form of the exponential utility function used to characterize the continuous attributes is

$$U(x) = a - b \exp(-rx) \qquad \text{(D-1)}$$

The three functions used for the calculation of single attribute utility functions are: cal_s_util(), cal_risk() and mid_parameter(). These three functions are described below:

cal_s_util(). This function reads the high, low, and median values of the attribute and estimates the risk constant using the function cal_risk(). The function mid_parameter() is then called to compute the continuous utility function constants a and b.

cal_risk(). This function evaluates the root of the function

$$f(r) = 0.5 + 0.5 \exp(-r(V^{*} - V_0)) - \exp(-r(V_{mid} - V_0)) \qquad \text{(D-2)}$$

The function is zero for $r = 0$, negative for small values of $|r|$, and positive for large values of $|r|$. The function first constrains r to be positive or negative depending on whether V_{mid} is above or below the arithmetic mean of V^* and V_0. After finding values for which f is positive and negative, cal_risk() performs a binary search between those points to find the value of r that yields $f = 0$. The function fn_val() is called to calculate each value of f during the binary search.

fn_val(). This function calculates the value of $f(r)$ using Equation (D-2) given the lowest, highest and the median values as well as current estimate of the risk constant.

mid_parameter(). Once the value of r is known, a and b can be calculated by the following set of equations :

$$\begin{aligned} 0 &= a - b \exp(-r\, x_0) \\ 1 &= a - b \exp(-r\, x^*) \end{aligned} \tag{D-3}$$

Solving for a and b yields

$$\begin{aligned} b &= 1 / \{\exp(-r\, x_0) - \exp(-r\, x^*)\} \\ a &= b\ \exp(-r\, x_0). \end{aligned} \tag{D-4}$$

After calculating a and b, mid-parameter() stores them in the U structure of that attribute.

2. Discrete Utility Functions

In some cases, the shelter attributes cannot take on a continuous range of values. These attributes are defined by a finite number of states. When the allowable states of a discrete attribute are mutually exclusive, the utility values associated with the attribute are defined by a Type I discrete utility function. Discrete attributes that can satisfy more than one state at a time, on the other hand, are defined by Type II discrete utility functions. For Type II discrete attributes, the utility value of the attribute is taken to be the sum of the utility values associated with the applicable states. In the current ASEM hierarchy, the discrete attributes are modularity and habitability. Modularity has a Type I discrete utility function, and habitability has a Type II discrete utility function. There are two functions — namely IE_list_mod() and IE_list_int() — that maintain lists of possible states for modularity and habitability, respectively. The function discrete_util() calculates the utility for any of these attributes. A brief description of these functions follows.

IE_list_mod(). This function stores the names of the different Type I attribute states and their respective utility values in a structure of type D_NODE. The function also returns a pointer to the list of states.

IE_list_int(). This function makes a list of states for the Type II attribute habitability. The function stores the names of the possible states for modularity and their corresponding utility values. When two or more states apply to the shelter concept, the utility values corresponding to the applicable states are added. Thus, the utility values of all of the individual states must sum to 1.0. The function also returns a pointer to the list of states.

discrete_util(). This function gives user a choice to enter the state of the attribute after displaying all the possible states. For Type I utility functions, discrete_util() reads the utility value corresponding to the user's choice and updates the variable "value" of the structure DU. For Type II discrete attributes, the utility values are summed according to the user's choices before the variable "value" of structure DU is updated. The function also stores the attribute states applicable to the current shelter concept in the structure make_choice.

C. PLOTS OF SINGLE ATTRIBUTE UTILITY FUNCTIONS

After the individual utility function parameters are calculated, ASEM gives the user the option to plot any single attribute utility function. The value of the attribute is shown on the X-axis and the value of the utility on a 0 to 100 scale is displayed on the Y-axis. A brief description of the functions used in plotting the single attribute utility functions is given in the following paragraphs.

show_utility(). This function calls show_name() to graphically display the entire hierarchy. After the user selects a low level attribute for plotting, the function retrieves the data structures related to the desired attribute. The function single_util_graph() is then called to plot the utility function of that attribute.

single_util_graph(). Given a pointer to a structure of type K for any lowest level attribute, this function displays the plot of its utility function. It divides the interval (lowest value, highest value) in forty parts and then stores the utility of each point, using the function util_val(), in an array. The function then calls the graphics library function LinePlotData() to plot that array. The function also allows the user to save the plot to a file of user's choice.

util_val(). Given a pointer to a structure of type U, util_val() calculates the attribute utility using the formula

$$U(x) = a - b \exp(-r\, x) \tag{D-5}$$

The parameters a, b , and r are stored in the type U structure that is linked to the attribute.

D. EVALUATION OF SCALING CONSTANTS

Two different approaches are used to evaluate the scaling constants: the indirect approach and the direct approach (see Section IV.B.5). The ASEM function method1_scale() implements the indirect approach and the function method2_scale() implements the direct approach. The indirect approach is used to evaluate the scaling constants for lowest level attributes that have continuous utility functions. The direct approach is used to evaluate scaling constants for higher level attributes and for all discrete-valued attributes. The function gen_scale() determines the location of the attribute in the hierarchy and then applies either the indirect or direct approach to evaluate the scaling constants. A brief description of these functions follows.

gen_scale(). The argument to this function is the pointer to the root node. It recursively visits each and every level and first looks for the attribute with the highest preference at this level. If this attribute is at the lowest level in the current branch of the hierarchy and has a continuous utility function, the function method1_scale() is called to evaluate the scaling constant of the attribute. Otherwise, the function method2_scale() is used to evaluate the scaling constants. Finally, gen_scale() calls the function multi_util() to adjust the scaling constants based upon whether the attributes are additive or multiplicative.

method1_scale(). After using the direct approach to calculate the scaling constant for one of the attributes at the current level, all other attributes are evaluated using the indirect approach. Using the procedure described in Section IV.B.5.b, the attributes at the current level are considered two at a time, and lotteries are constructed to determine pairs of attribute values for which the DM is indifferent. Based on the results of the lottery selections, the scaling constant for each attribute is evaluated using Equation (IV.B.5.3).

method2_scale(). This ASEM function uses the Direct Approach to evaluate the scaling constant of one attribute ($e.g., x_1$) at a given level in the hierarchy. The following lottery is offered to the decision maker (DM):

$$\{x_1^*, x_2^0, \ldots, x_n^0\} \sim \langle \{x_1^*, x_2^*, \ldots, x_n^*\}, \{x_1^0, x_2^0, \ldots, x_n^0\}; p \rangle \qquad \text{(D-6)}$$

That is, two options are given to the DM: (1) a probability p of achieving the best values of all the attributes at the current level and a probability of $1 - p$ of getting the worst values of all the attributes at the current level versus (2) the certainty of having the best value of attribute x_1 along with the worst values of all the other attributes. The DM is asked for the probability that makes him/her indifferent between the two options. The scaling constant for attribute x_1 is assigned the value of the indifference probability ($i.e., k_1 = p$).

E. CONTOURS OF OVERALL UTILITY

This module of ASEM shows the contours of overall utility after fixing all but two attributes. The user is given three graphics output options: screen display, HPGL printer file, or both. Once the type of display is selected, two attributes must be selected to generate the contour plot. The screen display of the contour shows the contours of overall utility as well as the individual utility plots of the two selected attributes. The function used for contour plotting is make_contour() which calculates the numerical values to be plotted and saves it in an array ContourMap. The function show_graph() is called to plot the contour window followed by the functions single_util_contour1() and single_util_contour2() to plot the individual utility functions of the two selected attributes. Mouse support is provided by the function zoom_mouse(), which zooms any of the three graph windows to fill the entire screen. Two additional functions, make_contour_pr_sc() and show_graph_pr_sc(), are modified versions of make_contour() and show_graph(), respectively, in order to provide both screen and graphics file output. Brief summaries of the functions used to display the contour plots are provided in the following paragraphs.

plot_info(). This function displays the three graphics display options and asks for the user's response.

make_contour(). This function calculates all the utility values for 30 by 30 grid of points over the ranges of the two selected attributes. The function also calculates a suitable contour interval for the plots based on the range of overall utilities in the domain of the two selected attributes. The function zoom_mouse is then called to display the plots.

zoom_mouse(). This function calls show_graph() to display the contours window and the single attribute utility plotting functions to display the individual attribute utility functions. Clicking the left button of the mouse locates a window and then displays that window in as a full screen plot. Clicking the left button of the mouse brings back the original screen. The right mouse button terminates the display screen.

show_graph(). This function fixes the size of the windows for plotting, and then uses array ContourMap to plot the contours. The function also displays a legend explaining the values of the contour lines. Finally, the functions single_util_contour1() and single_util_contour2() are called to display the single attribute utility plots of the two selected attributes.

single_util_contour1() and single_util_contour2(). These two functions are similar to the function single_util_graph() described in Section C of this appendix. The only modifications are that the windows are smaller in size and the axes are aligned with the axes used in the contour window.

F. CALCULATION OF OVERALL UTILITY

The overall utility module of ASEM calculates the mobility, cost, shelter performance, and survivability utility values along with the overall shelter utility. First, the name of the file containing the attributes of a specific shelter concept is requested. The contents of the concept attribute file are read through a call to the function read_overall(). Next, the function utility_graph() is called to compute the utilities of each child of the root node (*i.e.*, mobility, cost, shelter performance and survivability) as well as the root node itself (*i.e.*, overall utility). Additional functions are then called to calculate the values of selected high level shelter attributes. These high level attributes are supplementary physical quantities that may be of interest to the DM. The high level attributes included in the current version of ASEM are the number of worker-days needed to assemble a given quantity of shelters and the number of C-130s needed to transport a given quantity of shelters. The functions used in the overall utility module of ASEM are summarized in the following paragraphs.

utility_graph(). The utility_graph() function recursively goes to each level, starting at the lowest level, and first checks whether the overall utility at that level is additive or multiplicative.

A value 0 of the variable ad_mu in the header node indicates multiplicative utilities and a value of 1 indicates an additive overall utility. For the multiplicative case, the interaction constant, k, is stored in the header node variable "inter". The utility of the root node is a function of the utility of mobility, cost, shelter performance and survivability, whose utility in turn depend upon the attributes at a lower level. Thus, recursively calculating utility from the bottom level towards the highest level yields the overall utility. This function calls the function util_val() to calculate the utility value of a single lowest level attribute with a continuous utility function.

util_val(). This function calculates the utility of a particular value of a single attribute with continuous utility function. Based on the parameters a, b, and r it uses either an exponential or linear utility function formula to calculate the single attribute utility.

days_for_housing(). This function calculates the total number of worker-days needed to assemble 50,000 $feet^2$ of usable floor space. This quantity of floor space corresponds to about 80 small shelters or approximately 10 portable hangars.

number_C130(). This function calculates the number of C-130s required to transport 50,000 $feet^2$ of usable floor space.

APPENDIX E

R-VALUE TRADE STUDY

A. COOLING LOAD CALCULATIONS

This appendix presents a preliminary assessment of the cooling and heating load requirements for FOPs. In the design of equipment to handle cooling loads, transient analysis are used because the instantaneous heat gain in a structure varies with time due primarily to the strong temporal variation of solar radiation. At any given time, the difference in the heat gained by the structure and the heat removed by the cooling equipment may be large. This difference is due to thermal lag, where the structure and the contents of the structure store heat and subsequently release this heat to the circulating air at a later time as heat is removed by the cooling equipment.

In the discussion of cooling load calculations, it is important to differentiate between three terms: heat gain, cooling load, and heat extraction rate. Heat gain is the rate at which energy is transferred or generated within the space. This energy includes both sensible and latent heat and usually occurs in one of the following areas:

1. Solar radiation through openings.
2. Heat conduction through boundaries.
3. Sensible heat convection and radiation from internal objects.
4. Ventilation and infiltration air.
5. Latent heat gains generated within the space.

The cooling load is the rate at which energy must be removed from the space to maintain the design conditions. This rate is in general different from the Heat Gain due to the previously mentioned phenomenon of thermal lag.

The Heat Extraction Rate is the rate at which energy is removed from the space by the cooling equipment. This rate is equal to the cooling load when the space conditions are constant and the cooling equipment is operating. This is rarely true because the cooling equipment usually operates in a cyclic manner as dictated by the control system.

The calculation of heat transfer through the boundaries of a space usually involves the solution of a two-dimensional differential equation with non-linear and time-dependent differential equation with non-linear and time-dependent boundary conditions. Even with simplifications that allow the differential equation to be solved by Fourier series solutions, the calculation of design cooling loads is difficult without the use of a digital computer.

The Cooling Load Temperature Difference (CLTD) method is a simplified design method that makes extensive use of tables that were developed using the Fourier series solution of the transient heat transfer differential equation [ASHRAE, 1977]. The method specifies the cooling load for a particular boundary based on the surface area A, overall heat transfer coefficient U, and the *CLTD* for the boundary, which is obtained from the appropriate table. The CLTD accounts for the thermal lag of the boundary as well as the lag due to radiation of part of the energy from the interior of the boundary to objects within the space. The cooling load of a given boundary at time θ is expressed as:

$$\dot{q}_{\theta} = UA\,(CLTD)_{\theta} \tag{E-1}$$

where U = overall heat transfer coefficient, A = area, and *CLTD* = temperature differential, which gives cooling load at time θ.

As previously mentioned, the CLTD method makes extensive use of tables for the calculation of the cooling load. One of the primary tables used in the CLTD calculations provides the CLTD value for a wall, based on the solar time, wall orientation, and group classification of the wall. The group classification of a wall is based on its overall coefficient of heat transfer and its thermal inertia or the amount of thermal lag the wall introduces into the structure. Walls that have more mass per unit area tend to store thermal energy and subsequently release it over a period of time. This effect is usually desirable because it "shaves" the peak off the peak cooling load requirement for the structure and allows the installation of cooling equipment rated at lower capacities. The CLTD tables are constructed for "typical" wall construction groups. The Group G wall had the lowest mass unit per area of all the wall groups, and thus was the closest to the shelter materials. By choosing a Group G wall, or one with low mass per unit area values, no credit is taken for the cooling load peak "shaving" and thus the resulting calculations are conservative.

The overall cooling load is the sum of the solar conduction and radiation gain (calculated with the CLTD method), the gain due to equipment, the gain due to personnel, and the gain due to outside air ventilation. A sample cooling load calculation for a generic small shelter using the CLTD method and accounting for the other sources of heat gain is given in Example E.1.

B. HEATING LOAD CALCULATIONS

As with the heat gain, the heat loss of a structure is transient because the outdoor temperature, windspeed and direction, and solar radiation are constantly changing. During the coldest months, however, sustained periods of cold, cloudy, and stormy weather may occur with very little change in outdoor temperature. In this situation, the heat loss from a space will be relatively constant. Therefore for design purposes, the heat loss is usually estimated for this worst case steady state condition using some reasonable design temperature. Equations (E-2) and (E-3) give the heat loss through the space boundaries and the heat lost warming the outside ventilation/infiltration air, respectively. In heating load calculations it is acceptable practice to not take credit for internal heat sources.

$$\dot{q} = UA\,(t_i - t_o) \tag{E-2}$$

EXAMPLE E.1 COOLING LOAD CALCULATION FOR GENERIC SMALL SHELTER

SHELTER DIMENSIONS

$L = 3.65\ m$

$W = 2.29\ m$

$H = 2.29\ m$

$TO = 40.5\ degrees$ C — Avg. outsite temperature (C) on design day.

$TR = 25.5\ degrees$ C — Indoor design temperature.

$K = 1$ — Color correction factor.

$LM = 0\ degrees$ C — Latitude month correction, 0 = (40 *degrees* N. Lat. on 21 July).

Group G wall

Roof 1 without susp. ceil.

$U = 1.306\ (watt/m^2\ C)$

$R_{val} = 1/U$ — Unit thermal resistance (R-Value)

$R_{val} = 0.77\ (C \times m^2/watt)$

$CLTD_{nw} = 31$ C

$CLTD_{se} = 15$ C

$CLTD_{ne} = 14$ C

$CLTD_{sw} = 34$ C

$CLTD_{roof} = 33$

$CLTD_{floor} = 9.44$ C

NORTHWEST WALL

$A = HW = 5.24\ m^2$

$CLTD = CLTD_{nw}$ or $CLTD = 31$ C

$CLTD_{corr} = (CLTD + LM)\ K + (25.5\ C - TR) + (TR - 29.4\ C) = 42.1$ C

$\dot{q}_{nw} = U\ A\ CLTD_{corr} = 288.3\ watts$

SOUTHEAST WALL

$A = HW = 5.24\ m^2$

$CLTD = CLTD_{se}$ or $CLTD = 15$ C

$CLTD_{corr} = (CLTD + LM)\ K + (25.5\ C - TR) + (TO - 29.4\ C) = 26.1$ C

$\dot{q}_{se} = U\ A\ CLTD_{corr} = 178\ watts$

NORTHEAST WALL

$A = HL = 8.36\ m^2$

$CLTD = CLTD_{ne}$ or $CLTD = 14$ C

$CLTD_{corr} = (CLTD + LM)\ K + (25.5\ C - TR) + (TO - 29.4\ C) = 25.1$ C

$\dot{q}_{ne} = U\ A\ CLTD_{corr} = 274\ watts$

SOUTHWEST WALL

$A = HL = 8.36\ m^2$

$CLTD = CLTD_{sw}$ or $CLTD = 34$ C

$CLTD_{corr} = (CLTD + LM)\ K + (25.5\ C - TR) + (TO - 29.4\ C) = 45.1$ C

$\dot{q}_{sw} = U\ A\ CLTD_{corr} = 492.3\ watts$

ROOF

$A = WL = 8.36\ m^2$

$CLTD = CLTD_{roof}$ or $CLTD = 33$ C

$CLTD_{corr} = (CLTD + LM)\ K + (25.5\ C - TR) + (TO - 29.4\ C) = 45.1$ C

$\dot{q}_{roof} = U\ A\ CLTD_{corr} = 481.4\ watts$

EXAMPLE E.1 COOLING LOAD CALCULATION FOR GENERIC SMALL SHELTER (CONTINUED)

FLOOR

$A = WL = 89.97\,ft^2$

$CLTD = CLTD_{floor}$ or $CLTD = 9.44$ C

$CLTD_{corr} = (CLTD + LM)\,K + (25.5\text{ C} - TR) + (TO - 29.4\text{ C}) = 23.3$ C

$\dot{q}_{floor} = U\,A\,CLTD_{corr} = 254.4\ watts$

TOTAL Q FROM SOLAR CONDUCTION AND RADIATION

$\dot{q}_{scr} = \dot{q}_{ne} + \dot{q}_{se} + \dot{q}_{sw} + \dot{q}_{nw} + \dot{q}_{roof} + \dot{q}_{floor} = 1969\ watts$

HEAT GAIN FROM EQUIPMENT AND LIGHTS

$WATTS_{tot} = 6000\ watts$

$\dot{q}_{equip} = WATTS_{tot} = 6000\ watts$

HEAT GAIN FROM PERSONNEL

$PERSONNEL_{tot} = 3$

$\dot{q}_{person} = PERSONNEL_{tot}\ 146.5\ watts = 439.5\ watts$

HEAT GAIN FROM VENTILATION

$TO = 40.5$ C
$TR = 25.5$ C'
$RH_o = 3$

From Psychometric chart get h_i and h_o
$h_i = 11.67\ kcal/kg$
$h_o = 17.33\ kcal/kg$
$\dot{Q} = 0.56\ m^3/min\ PERSONNEL_{tot}$
Note: dry air weighs $1.2\ kg/m^3$
$\dot{q}_{vent} = \dot{Q}\ 60\ min/hr\ 1.2\ kg/m^3\ (h_o - h_i) = 796.2\ watts$

TOTAL COOLING LOAD

$\dot{q}_{TOTAL} = \dot{q}_{scr} + \dot{q}_{equip} + \dot{q}_{person} + \dot{q}_{vent} = 9204 watts$

$$\dot{q}_s = \dot{m}_o\, c_p\, (t_i - t_o)\ , \tag{E-3}$$

where t_i = internal temperature, t_o = outside temperature, $\dot{q}_s$ = sensible heat rate, $\dot{m}_o$ = mass flow rate, and c_p = specific heat capacity. A sample heating load calculation for the small shelter using Equations (E-2) and (E-3) is given in Example E.2.

C. TRADE STUDY

The R-value trade study calculations presented in this section use the CLTD method for the cooling load calculations and the summation of the transmission and ventilation losses for the heating load calculations to provide qualitative information on the merit of increased R-value for airmobile shelters.

EXAMPLE E.2 HEATING LOAD CALCULATION FOR GENERIC SMALL SHELTER

SHELTER DIMENSIONS

$L = 3.65\ m$
$W = 2.29\ m$
$H = 2.29\ m$
$t_o = 30\ degrees$ C — Avg. outsite temperature (C) on design day.
$t_i = 25.5\ degrees$ C — Indoor design temperature.
$\Delta t = t_i - t_o$
$U = 1.306\ (watt/m^2\ C)$
$R_{val} = 1/U = 0.77\ (C \times m^2/watt)$ — Unit thermal resistance (R-Value)

NORTHWEST WALL

$A = HW = 5.24\ m^2$
$\dot{q}_{nw} = U\ A\ T_{del} = 380.11\ watts$

SOUTHEAST WALL

$A = HW = 5.24\ m^2$
$\dot{q}_{se} = U\ A\ \ \Delta t = 380.11\ watts$

NORTHEAST WALL

$A = HL = 8.36\ m^2$
$\dot{q}_{ne} = U\ A\ \ \Delta t = 605.85\ watts$

SOUTHWEST WALL

$A = HL = 8.36\ m^2$
$\dot{q}_{sw} = U\ A\ \ \Delta t = 605.85\ watts$

ROOF

$A = WL = 8.36\ m^2$
$\dot{q}_{roof} = U\ A\ \ \Delta t = 605.85\ watts$

FLOOR

$A = WL = 89.97\ ft^2$
$\dot{q}_{floor} = U\ A\ \ \Delta t = 605.85\ watts$

HEAT GAIN FROM VENTILATION/INFILTRATION

$t_o = 30$ C
$t_i = 25.5$ C
$PERSONNEL_{tot} = 3$
$\dot{Q} = 0.56\ m^3/minute PERSONNEL_t = 1.68\ m^3/minute$
$v_O = 72\ m^3/kg$
$\dot{m}_o = \dot{q}/v_o = 0.0233\ kg/m^2 - minute$
$c_p = 240.5\ joule/kg$ C
$\dot{q}_{vent} = \dot{m}_o\ c_p\ (t_i - t_o)]/ = 519 watts$

TOTAL HEATING LOAD

$\dot{q}_{TOTAL} = \dot{q}_{ne} + \dot{q}_{se} + \dot{q}_{sw} + \dot{q}_{roof} + \dot{q}_{floor} + \dot{q}_{vent} = 3703 watts$

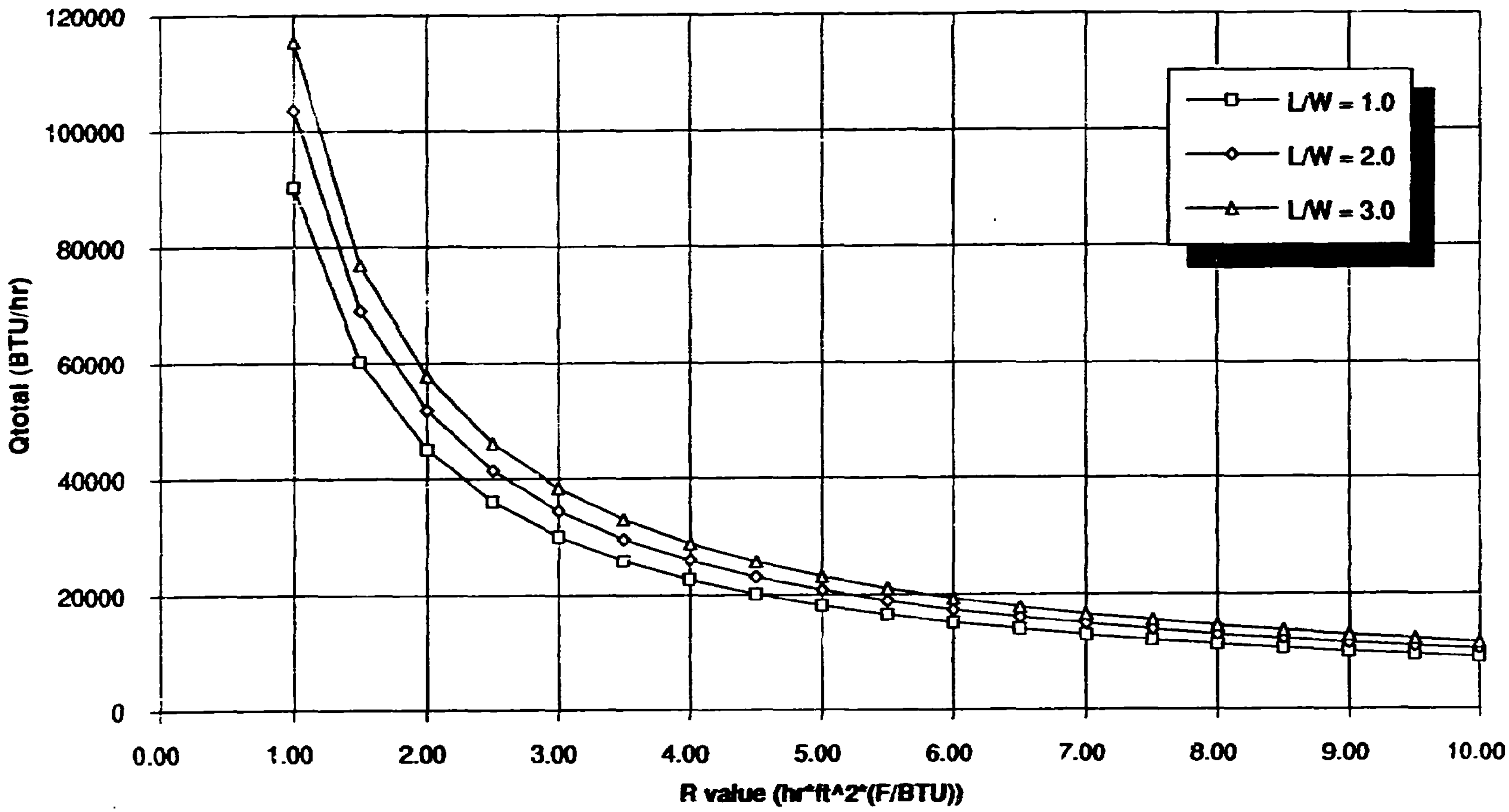


Figure E.1. R-Value Trade Study — Box Shelter

TABLE E.1. DESIGN CONDITIONS FOR SMALL SHELTER TRADE STUDY.

T_o	=	40.5 *degrees* C
T_i	=	25.5 *degrees* C
K	=	1
LM	=	0
h_o	=	17.44 *kcal/kg*
h_i	=	11.67 *kcal/kg*

Figure E-1 plots $\dot{q}_{total}$ of the generic small shelter used in the example calculations as a function of the R-value of the shelter panels. This information was used to develop the utility function for the ASEM code. Table E.1 summarizes the design conditions. The family of L/W curves varies the length to width ratio of the shelter while holding the total shelter volume constant. The shelter was oriented with the long sides facing SW and NE and the short sides facing NW and SE. By increasing the L/W ratio, we increased the area of the sides facing SW and NE, and thus increased the total cooling load for the shelter (the critical directions of course depend on values that we assumed in our design conditions, such as latitude, time of year, etc.). The two important points to note about this plot are: (1) the effect of shelter orientation, and (2) the diminishing returns (*i.e.*, lower cooling loads) for R-values beyond 5.0.

APPENDIX F

BASIC SHELTER GEOMETRY OPTIMIZATION

The selection of the geometry of a shelter requires consideration of many attributes, including function, constructability, usability, structural efficiency, and cost. Typical shapes include boxes, arches, and triangular prisms. For each shape, there are an infinite number of designs based on the independent geometric variables. There are, however, certain proportions that will maximize design efficiency. A study was undertaken to identify optimum proportions for several simple shelter objective functions. These results provide a starting point for concept selection and, more importantly, an understanding of shape optimization penalties associated with each candidate geometry. Formal structural optimization should be performed on the down-selected concepts that emerge from this project.

Two series of optimization analyses are included in this appendix. The first identifies the proportions that minimize the exposed surface area of eight basic geometric shapes. The second analysis is a simplified version of a shelter shotline analyses in which the damage function is related to presented area.

A. SHAPE OPTIMIZATION — MINIMIZATION OF EXPOSED SURFACE AREA

Geometries of different shelter types were examined to determine the optimum dimensions that minimize the surface area required for a given volume. The method does not take into account the volume usability (functionality) or the implications of cost or efficiency of the structural system. The examples presented herein assume that roofs and walls have the same unit weight, so that minimum surface area is equivalent to minimum weight. The floor of the structure is not included in the computation of surface area.

The surface area minimization approach consists of defining the surface area, S, and volume, V, of a given shape with n basic parameters, $x_1, x_2, \ldots x_n$. A constraint equation is obtained by expressing one of the variables $x_1, x_2, \ldots x_n$, in terms of the volume, V, and the other n - 1 basic parameters. The substitution method is used to eliminate the constraint, yielding a function of n - 1 variables. A necessary condition for the solution to be a local minimum or maximum is that the partial derivations are all zero, *i.e.*

$$\frac{\partial S}{\partial x_1} = 0, \frac{\partial S}{\partial x_2} = 0, \ldots \frac{\partial S}{\partial x_{n-1}} = 0 \qquad \text{(F-1)}$$

These simultaneous equations are solved analytically. A numerical solution was also checked to ensure that the second derivation is positive for each local minimum. Once the optimum values of the parameters, $x_1, x_2, \ldots x_n$, have been found, a non-dimensional surface area efficiency, S_e, is defined as

$$S_e = S/V^{2/3} \qquad \text{(F-2)}$$

Therefore, for each shape there exists an optimal S_e^* that minimizes the surface area for a given volume.

Triangular Prism Example. For the case of a triangular prism, the surface area, S, is given as

$$S = x_1 x_2 + 2x_3 [x_2^2/4 + x_1^2]^{1/2} \tag{F-3}$$

and the volume, V, is

$$V = x_1 x_2 x_3/2 \tag{F-4}$$

where x_1 is the vertical height of the prism, x_2 is the width of the prism, and x_3 is the length of the prism. One of three possible constraint equations is

$$x_1 = 2V/x_2 x_3 \tag{F-5}$$

The substitution of the equality constraint Equation F-5 into the surface area equation, Equation F-3, yields

$$S = \frac{2V}{x_3} + \left[x_2^2 x_3^2 + \frac{16V}{x_2^2}\right]^{1/2} \tag{F-6}$$

The two simultaneous equations to be solved are

$$\frac{\partial S}{\partial x_3} = 0 = -2Vx_3^{-2} + \left[x_2^2 x_3^2 \frac{16V^2}{x_2^2}\right](x_2^2 x^3) \tag{F-7}$$

$$\frac{\partial S}{\partial x_2} = 0 = 1/2\left[x_2^2 x_3^2 \frac{16V^2}{x_2^2}\right]^{-1/2} [2x_2 x_3^2 - 32V^2 x_2^{-3}] \tag{F-8}$$

The solution of Equations F-7 and F-8 yield the values of the parameters x_2 and x_3 in terms of the volume, V. The volume, V, is removed with the constraint equation, yielding

$$x_2^* = 2x_1 \tag{F-9a}$$

and

$$x_3^* = \sqrt{2}\, x_1 \tag{F-9b}$$

where the asterisk denotes the optimum values. The surface area and volume of the optimum triangular prism as a function of x_1 are

$$S^* = 6x_1^2 \tag{F-10}$$

$$V^* = \sqrt{2}\, x_1{}^3 \tag{F-11}$$

The optimum non-dimensional surface area efficiency, S_e^*, is

$$S_e^* = S/V^{2/3} = 4.762 \tag{F-12}$$

Optimum Geometries. Eight different shapes were examined using the procedure described above. The results are summarized in Figure F-1. The triangular prism results are shown in the upper left-hand corner.

Of the eight shapes examined, the hemisphere is the most efficient shape, having a surface area efficiency of 3.[illegible] The least efficient shapes are the triangular prism and the rectangular parallelepiped (box), having a skin efficiency of 4.76. The surface area penalty associated with deviation from the hemisphere shape to the box shape is 24 *percent.* However, this theoretical penalty does not consider that the upper portion of the interior volume of the hemisphere may not be functionally usable space. Another observation from Figure F-1 is that the optimum length of the half cylinder is twice its radius. Also, the optimum box has a square base with dimensions equal to twice its height.

A visualization of these optimal proportions for six of the shapes in Figure F-1 is given in Figure F-2. Each of the shapes in Figure F-2 have equal interior volume and the plan and elevation views show the optimum scales according to the results in Figure F-1. Note that they all have a square or nearly square floor plan, with the largest exception being the triangular prism. Hence, if function allows, square to circular floor plans of the new shelters should be considered.

Surface Area Penalty. The results in Figures F-1 and F-2 provide unconstrained minimal surface areas (and hence weights) for each shape category. By computing the surface area efficiency (S_e) of existing shelters, we can quantify the surface area penalty as a percentage increase over the theoretical minimum. Figure F-3 illustrates the penalty for various ISO shelters. The ISO 2:1 is very close to the true optimal, whereas the ISO 1:1 has an 8% penalty. The penalties for the ACH and TEMPER are summarized in Figure F-4. These penalties are relatively small (8 *percent* and 3 *percent*, respectively); but suggest that some reductions in weight could be achieved if other constraints allow the shape to approach its true optimum for a given amount of floor space. Comparisons of the optimum shape surface area efficiencies *vs.* actual efficiencies for selected shelters are shown in Figure F-5.

B. SHOT LINE OPTIMIZATION

The vulnerability of different shelter shapes (both actual and optimal) was examined using a shotline approach. The shotline direction is defined, as shown in Figure F-6, by an angle, θ, with respect to the z axis and an angle, ϕ, with respect to the horizontal x-axis of the shotline projection onto the x-y plane. A shotline defined by the two angles, θ and ϕ, defines the direction vector of incoming projectiles or bullets.

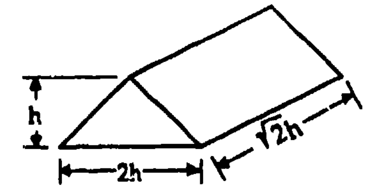
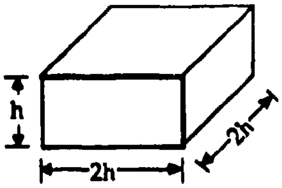
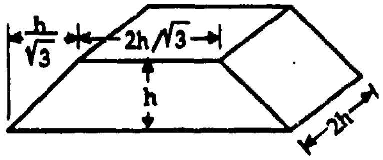
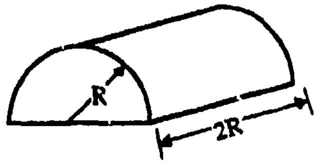
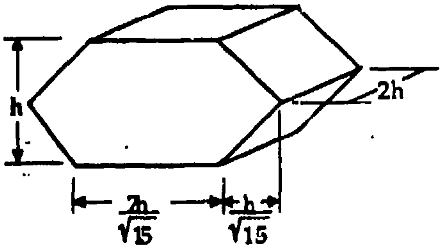
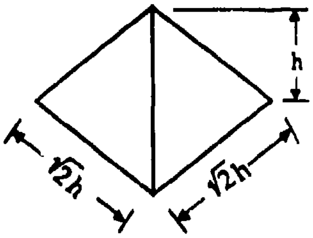
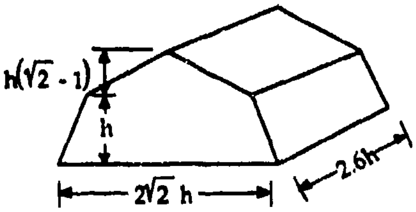
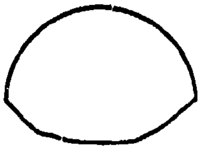
Shape	Opt. Skin Eff. $S/V^{2/3}$	Shape	Opt. Skin Eff. $S/V^{2/3}$
	4.76		4.76
	4.54		4.39
	4.71		4.54
	4.47	 Hemisphere	3.83

Figure F-1. Optimum Skin Efficiencies for Various Geometries.

The effective surface area, S_{eff}, of a shelter for a given shotline direction is defined as

$$S_{eff}(\theta, \phi) = S_{vis}(\theta, \phi)\, D(\beta) \qquad \text{(F-13)}$$

where $S_{vis}(\theta, \phi)$ is the presented (or visible) area of the structure for angles θ and ϕ, $D(\beta)$ is the damage function, and β is the angle of incidence between the shotline and the structure.

The effective area of the structure is found from

$$S_{eff} = \sum_{i=1}^{N} A_i \cos\beta \; g\left(\theta, \phi\right) D(\beta) \qquad \text{(F-14)}$$

where A_i is the area of one of the faces of the structure, and the summation is carried out over all faces. The angle, β, is calculated using the dot product of the unit shotline vector and the unit vector normal to the surface.

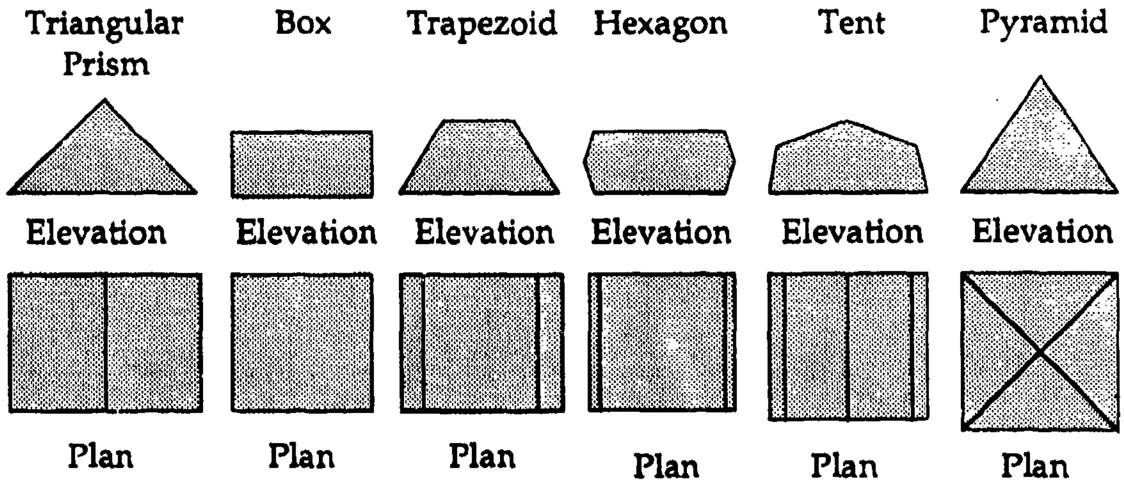


Figure F-2. Plan and Elevation Views of Optimum Shapes.

$$\cos\beta = \mathbf{n} \cdot \mathbf{r} \tag{F-15}$$

where the unit shotline vector, **r**, is

$$\mathbf{r} = \mathbf{i}\sin\theta_r\cos\phi_r + \mathbf{j}\sin\theta_r\sin\phi_r + \mathbf{k}\cos\theta_r \tag{F-16}$$

and the unit vector, normal to the surface of the area, A_i, is

$$\mathbf{n} = \mathbf{i}\,a_n + \mathbf{j}\,b_n + \mathbf{k}\,c_n \tag{F-17}$$

The visibility function $g(\theta, \phi)$ takes on a value of zero when cos β is negative and one when cos β is positive.

The effective surface area, S_{eff}, for each shape is determined for seventy-two horizontal angles (ϕ) between 0 and 2π, and eighteen vertical angles (θ) between 0 and $\pi/2$. The seventy-two by eighteen matrix of effective surface areas is stored in non-dimensional form (normalized by $V^{2/3}$) for later use. To ensure that the geometry has been correctly entered for use in the shotline computer program, views of the structure for various combinations of ϕ and θ are generated. Figure F-7 shows the visible surface area for a hemisphere for a ϕ value of 0 *degrees* with θ varying between 0 *degrees* (vertical) and 90 *degrees* (horizontal) in increments of 10 *degrees*. Figure F-8 shows similar views of a trapezoidal shelter for ϕ = 30 *degrees*. The MERWS and FSTFS shelters are shown in Figures F-9 and F-10, respectively, for ϕ = 45 *degrees*.

Different shotline threat potentials were examined by integrating the effective surface area matrices with selected probability distributions, $f(\phi, \theta)$

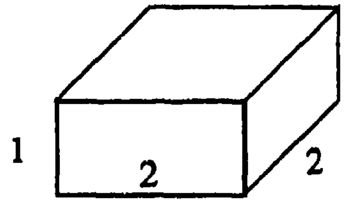
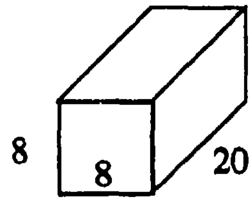
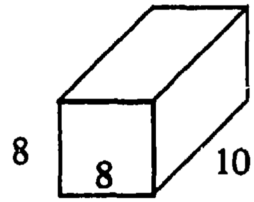
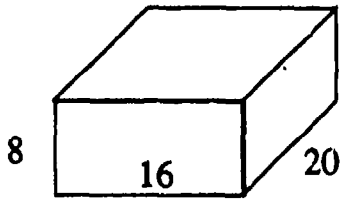
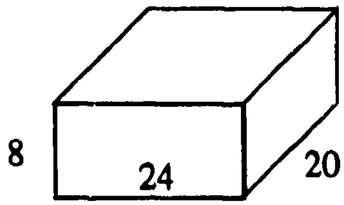
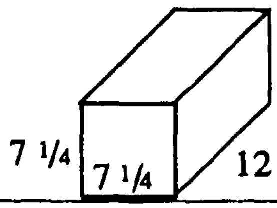
Shelter Type	Shape	$S/V^{2/3}$	Surface Area Penalty *(feet²) (percetage)*
Optimum Shape (no floor)		4.76	--
ISO 1:1		5.16	46.6 ft^2 (8.3%)
ISO 8 × 8 × 10		4.96	14.4 ft^2 (4.1%)
ISO 2:1		4.79	5.2 ft^2 (0.6%)
ISO 3:1		4.83	16.8 ft^2 (1.4%)
S280 S.G		4.98	16 ft^2 (4.5%)

Figure F-3. Surface Area Penalties for Existing Parallelpiped Shelters.

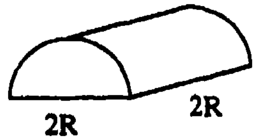
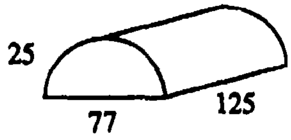
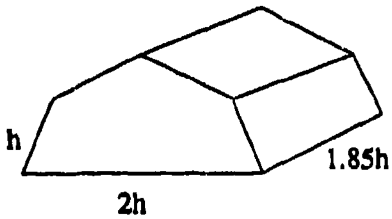
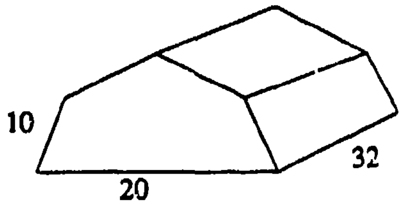
Optimum Shape		Typical Actual Shape		Surface Area Penalty	
	$S/V^{2/3}$		$S/V^{2/3}$	(ft^2)	%
 Aircraft Hanger (ACH)	4.39		4.80	13,688	8%
 TEMPER Tent	4.47		4.60	36.6	3%

Figure F-4. Surface Area Penalty for ACH and TEMPER.

$$\bar{S}_{eff} = \int_\theta \int_\phi S_{eff}\, f(\phi, \theta)\, d\phi d\theta \qquad \text{(F-18)}$$

where $\bar{S}_{eff}$ denotes the expected value surface area efficiency and $f(\phi, \theta)$ is the shotline probability density function. Four different threat conditions were examined, namely:

(i) ***Horizontal, Equally Likely:*** $f(\phi) = 1/2\pi$, $\theta = \pi/2$

(ii) ***Oblique (45 degrees), Equally Likely:*** $f(\phi) = 1/2\pi$, $\theta = \pi/4$

(iii) ***Vertical:*** $f(\phi) = 1$, $\theta = 0$

(iv) ***All Directions, Equally Likely:*** $f(\phi) = 1/2 \sin \pi \sin \phi$,

The above four probability density functions describe a horizontal threat (equally likely for any value of ϕ), an oblique threat (equally likely for any value of ϕ), a vertical threat (independent of ϕ), and the case of the threat equally likely from any above-ground direction.

The resulting $\bar{S}_{eff}$ for nineteen different shelter geometries have been developed for each of the four threat conditions and two damage functions: $D(\beta) = 1$ and $D(\beta) = \cos \beta$. For the case of $D(\beta) = 1$ no credit is taken for oblique impacts, corresponding to materials that fail through stretching of fibers and delamination (such as Kevlar®, Spectra®, and S-2 Glass). Oblique impacts generally have little effect until impact angles are greater than 45 *degrees* for these materials. The case $D(\beta) = \cos \beta$ is a conservative model of damage potential for penetration into materials that resist penetration through shearing and plugging.

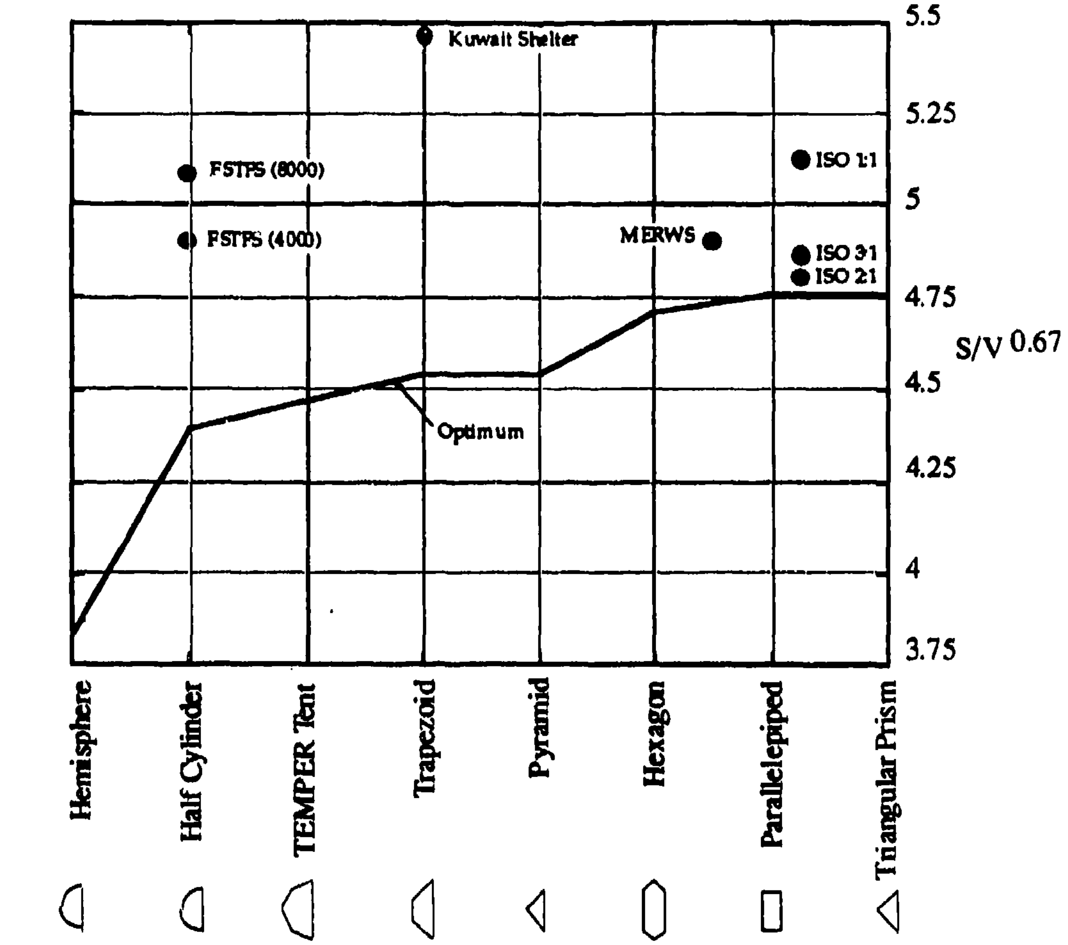
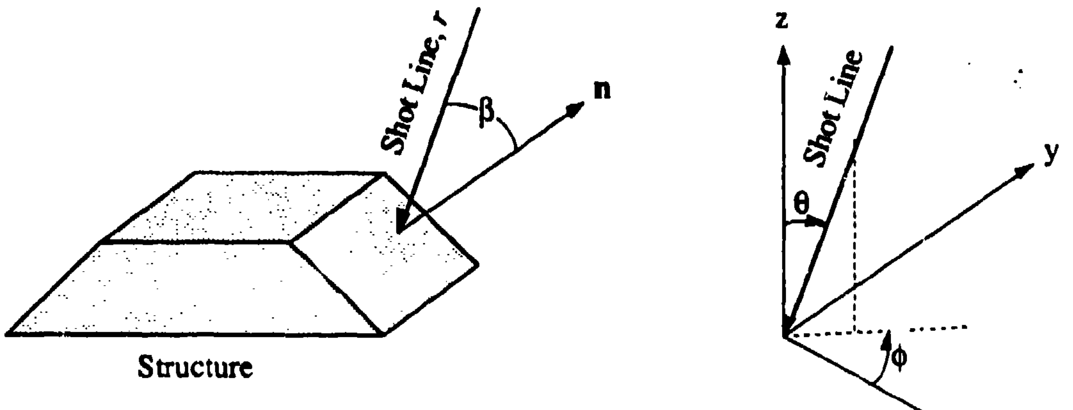


Figure F-5. Surface Area Efficiency — Actual Shelters *vs.* Optimum.



n = vector normal to structure surface.

β = angle between shot line and normal vector.

Figure F-6. Ballistic Shot Line.

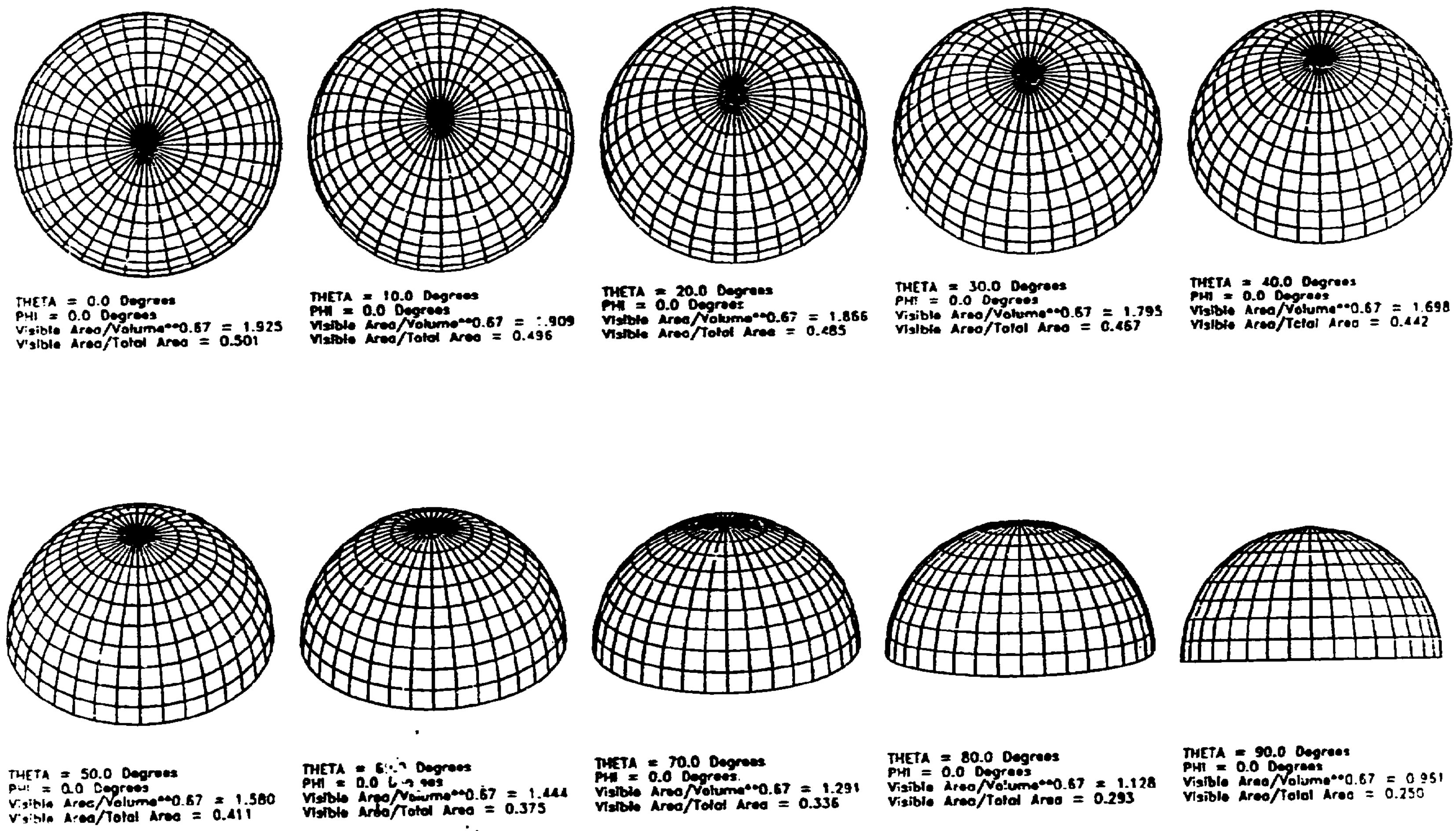


Figure F-7. Visible Surface Area for Hemisphere.

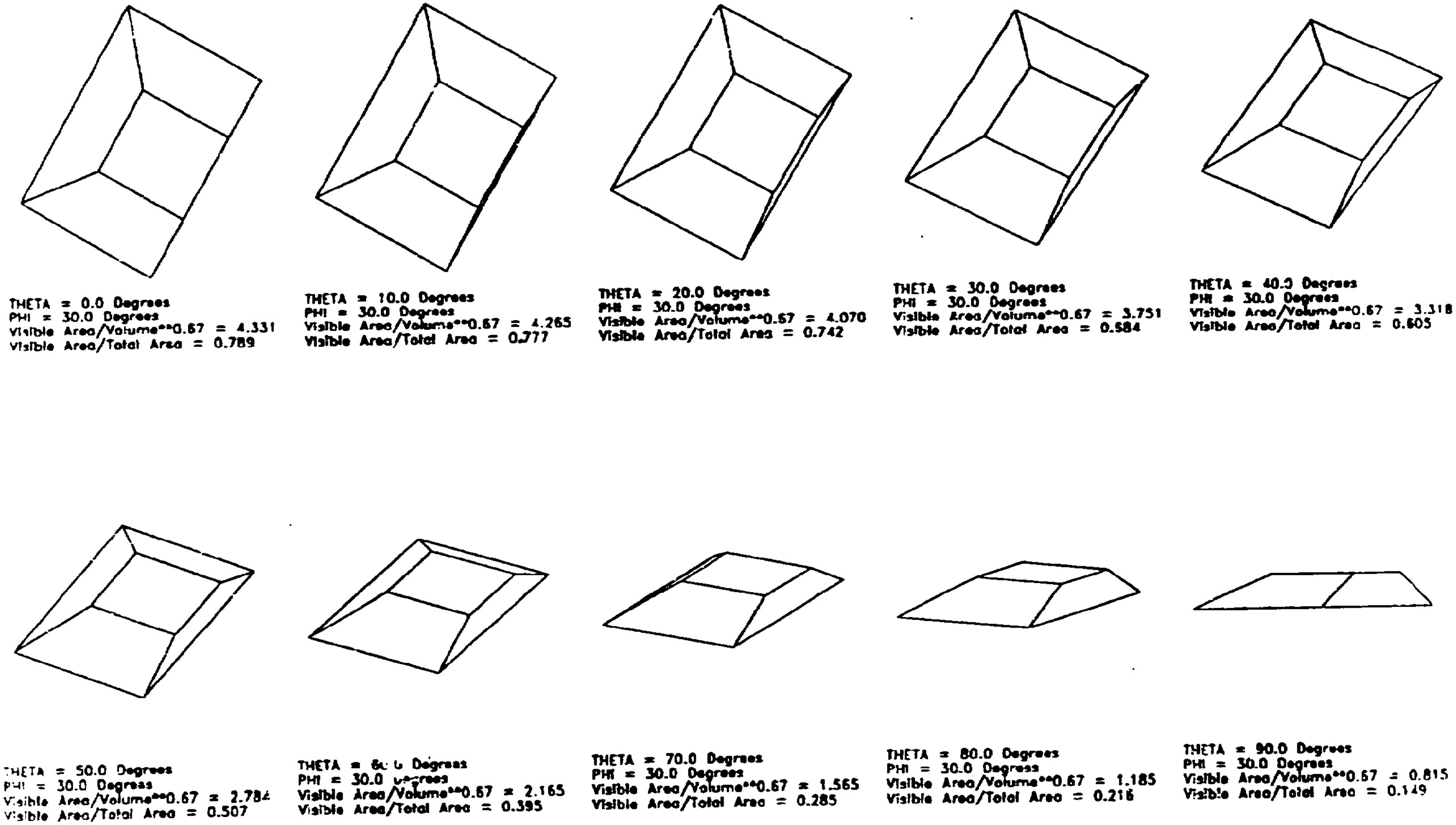


Figure F-8. Visible Surface Area for Trapezoidal Shelter.

Figure F-11 summarizes the results for $D(\beta) = 1$. Shelters with minimum $\overline{\Sigma}_{eff}$ for horizontal shotlines include the large area shelter shapes, such as the Kuwait, Aircraft, FSTFS 8000, and FSTFS 4000. These shelters have low horizontal profiles compared to their interior volumes. In contrast, these shelters have high $\overline{\Sigma}_{eff}$ for vertical and 45-*degree* shotlines. Of all the shapes, the hemisphere has the minimum $\overline{\Sigma}_{eff}$ for 45-*degree* and equally likely direction shotlines. The Kuwait shelter shape has the highest $\overline{\Sigma}_{eff}$ for vertical, 45-*degree*, and equally likely direction shotlines.

Figure F-12 summarizes the results for $D(\beta) = \cos\beta$. The $\overline{\Sigma}_{eff}$ for the cube equals 1.0 for the four threat directions. The plots follow the same trend as in Figure F-9, with some smoothing resulting from the $\cos\beta$ damage function.

These results represent simple first order shape optimization data useful primarily for concept synthesis and development. Detailed hardening and vulnerability analyses with validated damage models should be performed on the down-selected shapes.

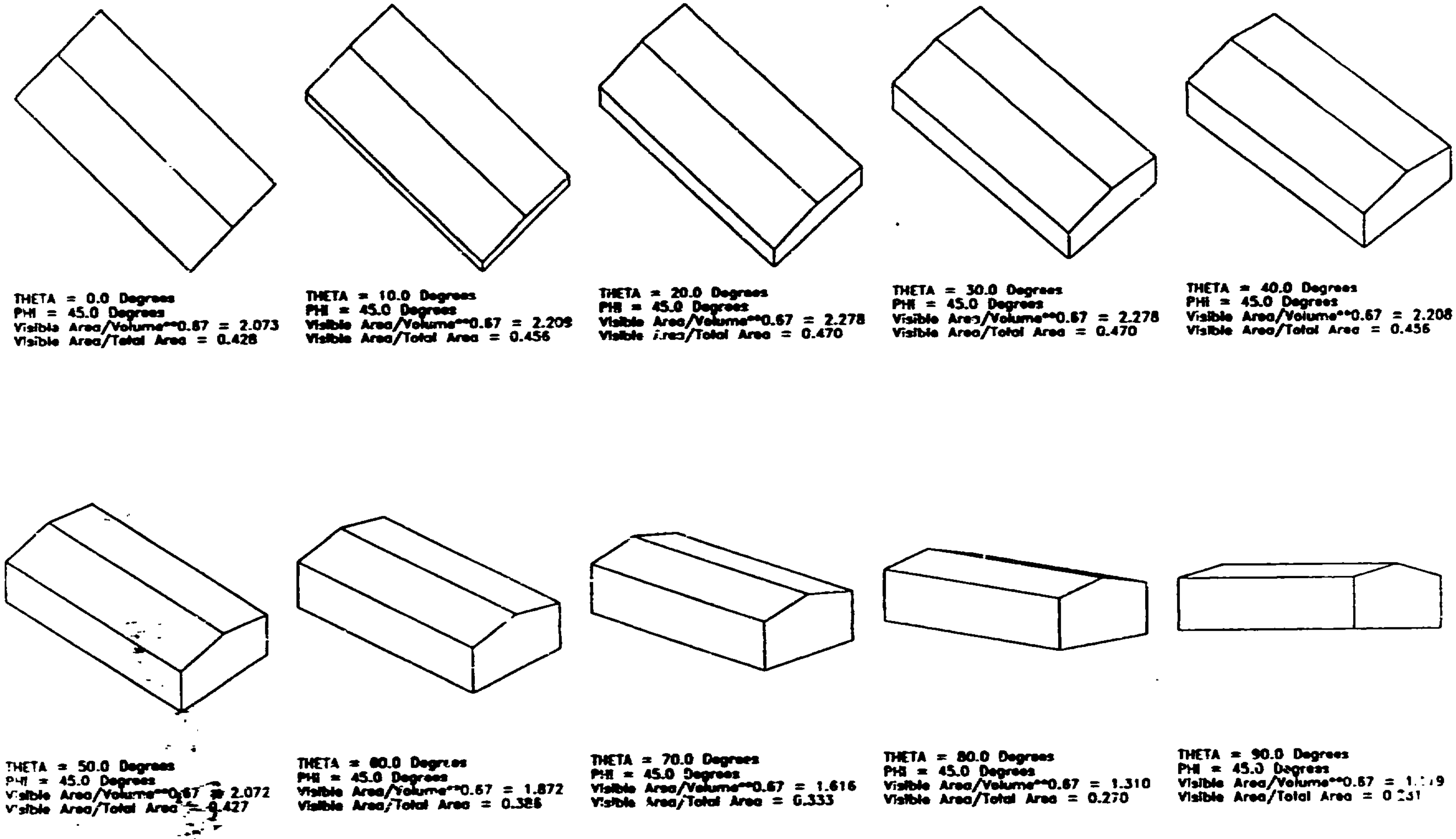


Figure F-9. Visible Surface Area for MERWS.

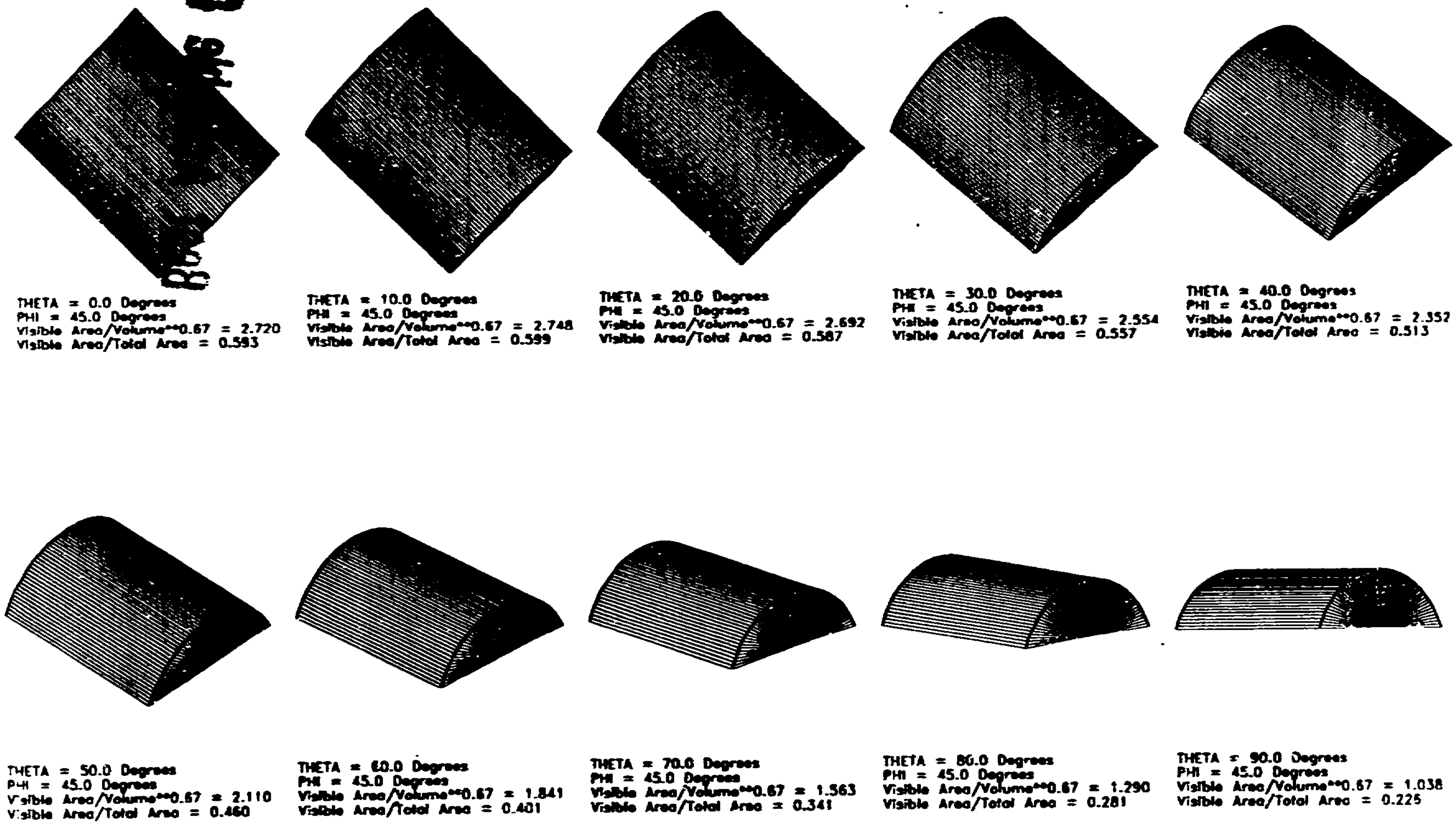


Figure F-10. Visible Surface Area for FSTFS (4000 *feet*^{2}).

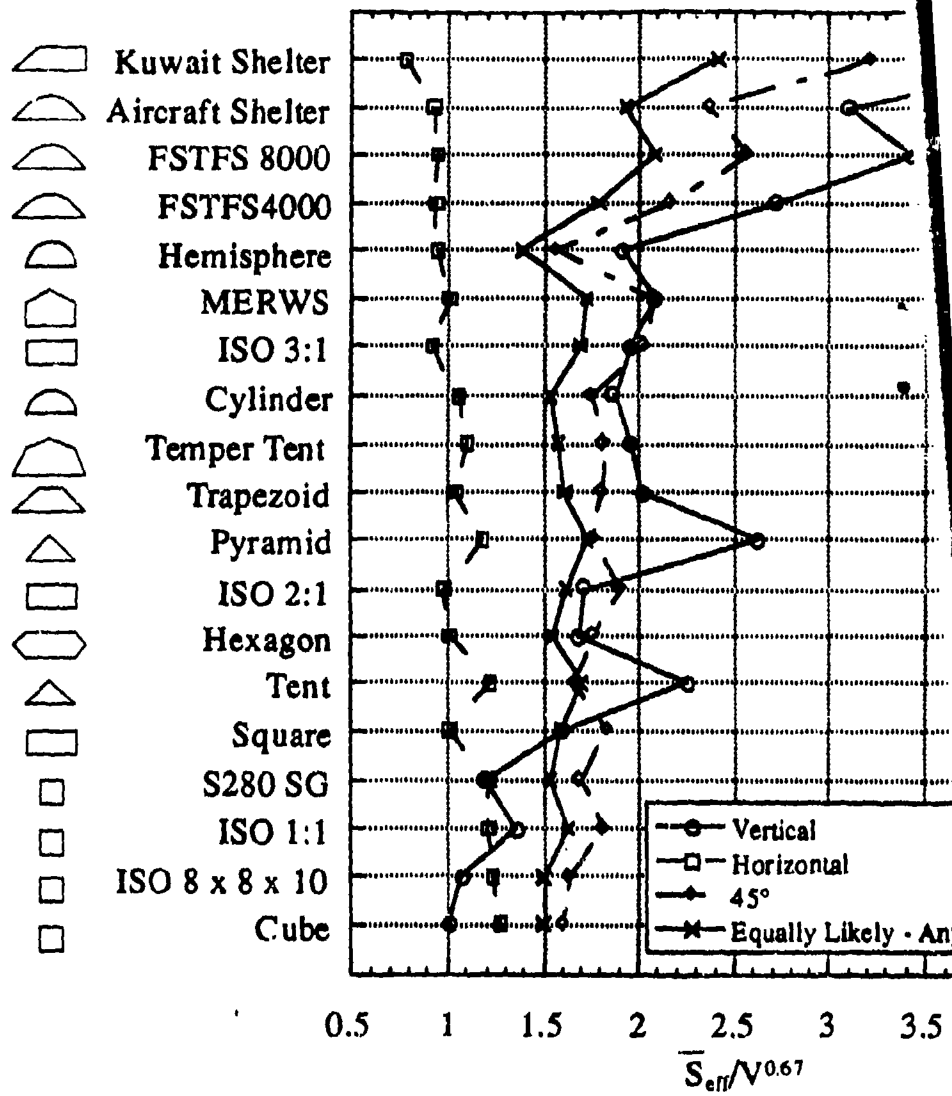


Figure F-11. Expected Value Surface Area Efficiencies for $D(\beta)$ =

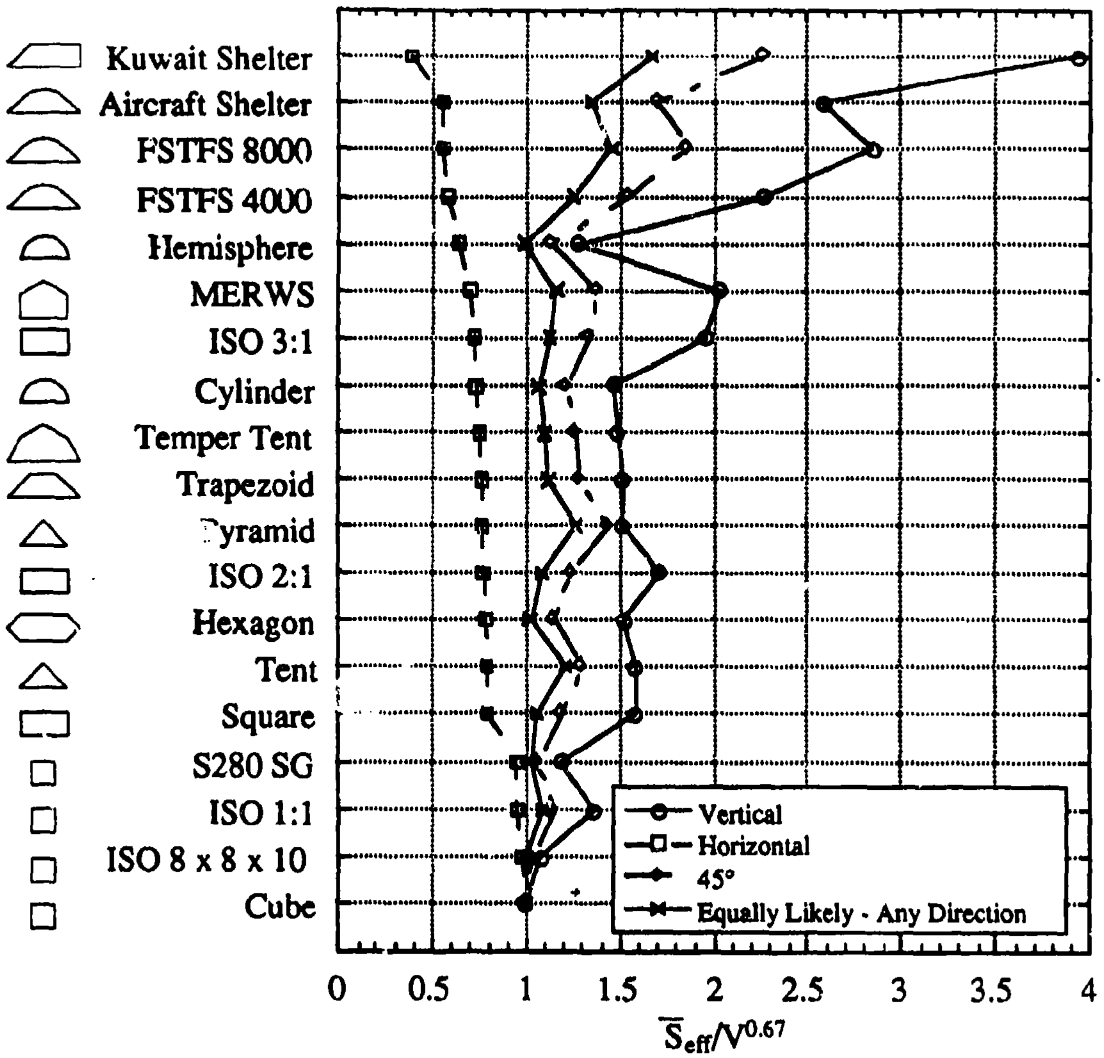


Figure F-12. Expected Value Surface Area Efficiencies for $D(\beta) = \cos\beta$.